Master's Thesis
석사 학위논문

Electronically Controlled Multi-color Optical Shutter with Metallic Nanostructure

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정보통신융합공학전공

DGIST

2017

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1]

01. 06. 2017

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Accepted in partial fulfillment of the requirements for the degree of Master of Science

01. 06. 2017

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MS/IC
201522015

이 영 진. Youngjin Lee. Electronically Controlled Multi-color Optical Shutter with Metallic Nanostructure, Department of Information and Communication Engineering. 2017. 54p.
Advisor Prof. Jae Eun Jang, Co-Advisor Prof. Chang-Hee Cho.

Abstract

Electrically tunable multi-color optical filter structure has been studied employing asymmetrical nanohole array design and a twisted nematic (TN) mode of liquid crystal (LC). Recently, some researches have been reported to get various color states in one unit cell structure, since it can be one of the most important solution for ultra-high integration density of some opto-electrical devices such as a semiconductor based image sensor or a display device. Nanometer level size hole arrays on metal film have shown extraordinary phenomenon, filtering effect on visible light due to surface plasmonic effect mainly. The filtering color can be changed by the control of environmental factors such as a refractive index, a dielectric constant or incident polarization direction. However, most of these control principle is not electrical methods, but the change of material property or mechanical principle, so that it is hard to apply this structure to various opto-electrical devices.

In this thesis, in order to solve these limitations, 2-dimensional (2D) asymmetric nanohole array design with electrical polarization rotator function employing a twisted nematic (TN) mode of liquid crystal (LC) has been suggested. Nanohole arrays having different structure factors of x and y axis were fabricated on aluminum film. This asymmetric nanohole array design allows to get two different principle colors and mixed states with modulation of incident light polarization, even if it is a structural fixed design. The polarization state is tuned electrically by TN-LC structure combined with the asymmetrically designed nanohole layer. The color tuning shift is larger than 100nm depended on the design layout of nanohole array. It is not easy to get this wide range color change by a control of refractive index of surrounding materials, generally. The functional ability as electrode of nanohole array on metal film and low driving voltage of TN cell mode can open high probability to apply to various electronic device concepts, such as dynamic display, variable information encoding, anti-counterfeiting.

Keywords: Electrically Tunable Multi-color Optical Filter, Nanohole Arrays, Liquid Crystal;

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I. Introduction

1.1 Motivation

Plasmonic nanostructure has been studied for color filter, biosensor, super-resolution imaging, energy harvesting due to its huge potential to manipulate light [1-10]. Especially, plasmonic color filter can replace conventional fluorescent color filter because it has some advantage such as straightforward process, cheap material cost, high optical efficiency, and high durability to external environment. Also, plasmonic color filter has been conducted to use its high resolution property in CMOS Image Sensor (CIS) [11].

Also, one of the key issues in the high resolution display is improvement of pixel system. These days, one pixel has RGB sub pixel to represent entire color. However, if one sub pixel can show variable color, we do not need conventional sub pixel system. Then, the resolution of display can be highly increased. In this point of view, to present various colors in one device is very important issue. For those reasons, we demonstrated a dynamic tunable multi-color device using plasmonic color filter and Liquid Crystal (LC) to realize novel color representation system.

1.2 Plasmonic Color Filter

1.2.1 Surface Plasmons

Surface plasmons are a special phenomenon when incident light meets the free electron of metal at the interface between two layer, dielectric material and metal film. This incident light excites free electrons to make evanescent waves. These wave propagate at the interface of metal and dielectric and exponentially decay inside the metal and dielectric material. However, light is hard to couple with free electron owing to the mismatch of their wave vectors. Following equation shows the mismatch problem between surface plasmon wave and incident light [12]. Both dielectric material and metal film influence surface wave property. k_{sp} represents the wave vector of surface plasmons and k_0 is the wave vector of the incident light in vacuum. ε_m and ε_d are dielectric constants of metal and dielectric, respectively. From this equation, it is clear that propagating electromagnetic waves cannot be directly converted to surface plasmons due to a mismatch of their wave vectors.

$$k_{sp} = k_0\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{1}$$

In order to solve this problem, there are many different ways and the most generally used methods are Kretschmann/Otto configurations and gratings.

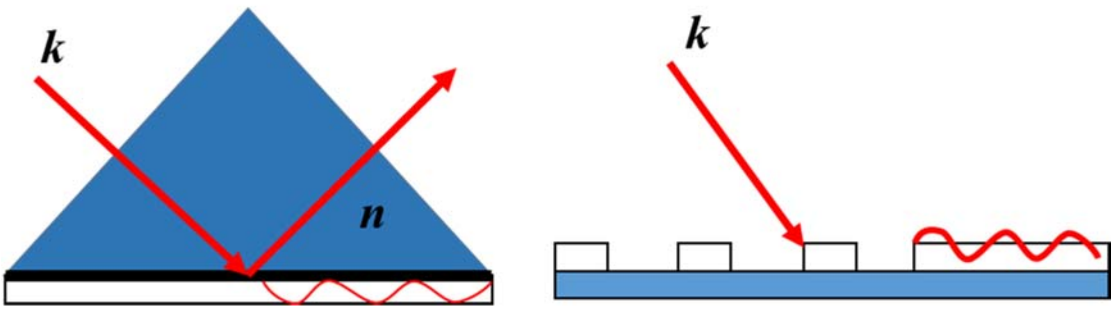


Fig 1.2.1.1 (a) Surface plasmon excitation using Kretschmann configuration. (b) Grating method to provide additional wave vector.

The Kreschmann configuration uses a prism to increase the refractive index of incident sides. When the light wave vector in the prism side is same to SPP wave vector on an air-metal surface, tunneling of resonant light occurs, then light can couple to surface polaritons [13]. Also, gratings in metal layer can contribute to excitation of SPP. The geometric effect of grating makes an additional wave vector solving mismatch problem of momentum. Additional wave vector helps incident light to couple with surface plasmon wave.

Plasmonics are the conception to include surface plasmons, and it cover light-matter interaction in nanoscale materials such as nanoparticles and nanostructures. At the nanoscale level, light can be freely modulated by external geometry factors. Many researches are conducted due to its potential power in diverse applications such as metamaterials, biomedicine, energy and photonic computing.

1.2.2 Color Filter Using Nanohole Arrays

There are many applications to concentrate desiring light using the property of plasmonics. Above all, plasmonic metal nanostructure is powerful candidate due to its simple fabrication step and various applications. Furthermore, in the many plasmonic structures, nanohole array is good candidate for color filter. Because it is easy to design desire color varying structure factors and it shows high efficiency of light conversion. In order to present specific color, the resonance property can be modulated by some geometry factors of the metal nanohole arrays structure such as thickness of metal film, shape of hole, and the periodicity between each hole. Therefore appropriate design factors are necessary to effectively transmit desire light. Above all, the spacing between holes is more important than other factors because it mainly influences the position of resonance point. Following equation presents the relation between position of resonance point and spacing factor.

$$\lambda_{peak(i,j)} = \frac{s}{\sqrt{i^2+j^2}}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m+\varepsilon_d}} \quad (2)$$

Where s is the spacing between the holes; ε_m and ε_d are the dielectric constants of the metallic and dielectric layers, respectively, and i and j indicate the scattering orders.

In addition, polarization dependent transmission can be achieved by asymmetric design [14-16]. If nanohole arrays are fabricated with different design factor for each direction of polarization, each polarized incident light can couple to their own structure. For example, rectangular arrangement of nanoholes having different spacing for x and y direction shows different colors according to their incident polarization. Therefore, different colors appears at one fixed device using these methods, although device still need additional component to change polarization state of incident light.

1.2.3 Dielectric Constant Sensitivity

Surface plasmon wave is the interaction between dielectric material and metal. If dielectric material is exchanged from air to other material, the resonance condition is also changed. The dielectric constant term is presented in equation 2. This phenomenon quickly appears, and very sensitive. Therefore, it can be used for sensing unknown material.

For example, plasmonic biosensor[17, 18] can detect unknown material when the surface of biosensor meets unknown material. If antibody layer is coated on surface of metal film, biosensor can easily detect the antigen and it has high sensitivity. Also, many researches are using dielectric material sensitivity to present variable and continuous colors in plasmonic color filter [19].

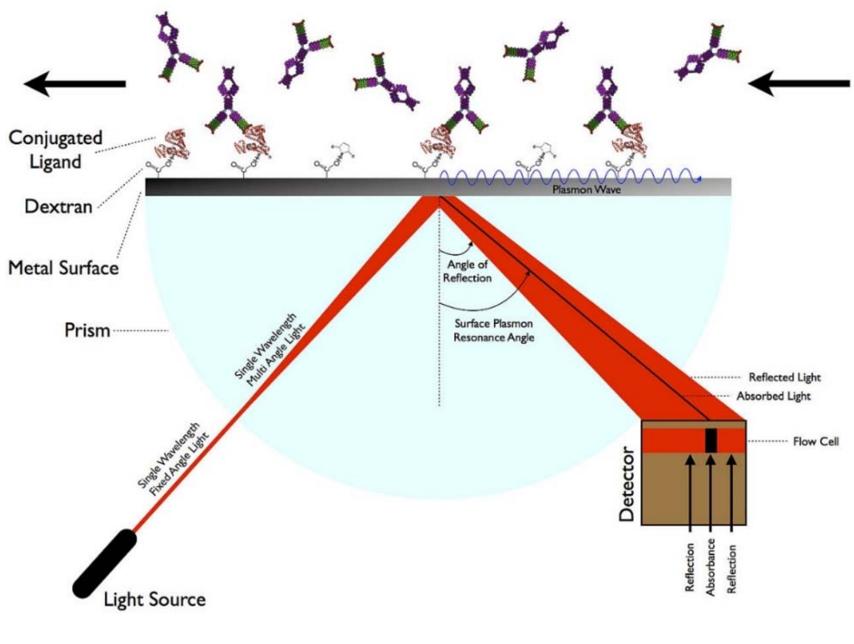


Fig 1.2.3.1 Bio-detection using surface plasmon resonance

1.3 Liquid Crystals

Liquid crystals are well known material due to its electro-optical and thermal-optical property and they have been used in various industry, such as liquid crystal displays, optical switches and attenuators for telecommunications, and optical phase arrays for beam steering, etc. They are very important material to human's life and many researches are currently conducted to improve the possibility of liquid crystal.

1.3.1 Property of Liquid Crystals

Liquid crystals (LCs) are unusual material having properties of both liquid and solid crystal. They can flow like a liquid but maintain some of the ordered structure of crystals. Also, LCs are attractive material due to its unique electro-optical property. When the electric field is applied, the direction of LCs molecule is tilted to special direction. And this phenomenon has been used in various applications such as electronic displays and optical switches.

The shape of LCs is diverse, and there are some phases such as nematic, cholesteric, smectic, and so on. In the LCs, the molecules tend to align along the same direction of neighborhood molecules. Not all molecules are aligned along a certain direction owing to their own motion and defects. Nevertheless, the average direction are considered to the entire orientation of LCs. The direction of LCs is randomly distributed without external ordering method and this direction is important property of LCs because of birefringence.

Birefringence means that a material has a refractive index with different polarization and propagation direction of light. As shown in the Fig 1.3.1.1, uniaxial materials have two different refractive index n_e and n_o. When the electric wave of light becomes perpendicular to director of LCs, LCs have the ordinary refractive index n_o. And if the electric wave of light becomes parallel to director of LCs, LCs have the extraordinary refractive index n_e. Uniaxial LCs are widely used in industry to modulate polarization state of light. Also, birefringence is a function of temperature.

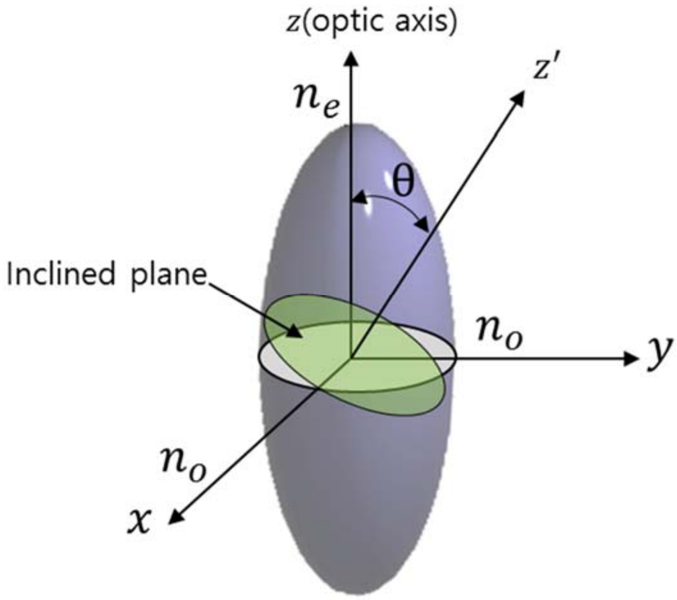


Fig 1.3.1.1 Birefringence property of liquid crystal

1.3.2 Polarization Rotator Using Liquid Crystal

The birefringence can be used to make polarization rotator. Twisted nematic (TN) mode is one of the popular polarization rotator. As shown in the Fig 1.3.2.1, TN mode changes the polarization of incident light to same direction of top polarizer. The twisted liquid crystal structure make the polarization rotation due to its adiabatic following [20]. Therefore, polarized light can pass the top polarizer and this system shows white state. However, with vertical alignment of LCs, incident light cannot be polarized and light is prevented by top polarizer and the system shows dark state.

But it is not easy to fix many LCs to same direction. In order to give ordering to LCs, alignment process is necessary. For alignment process, micro groove and chemical bonding can affect to the direction of LCs. Using alignment layer and rubbing process, average direction of LCs is controlled to specific direction [21, 22].

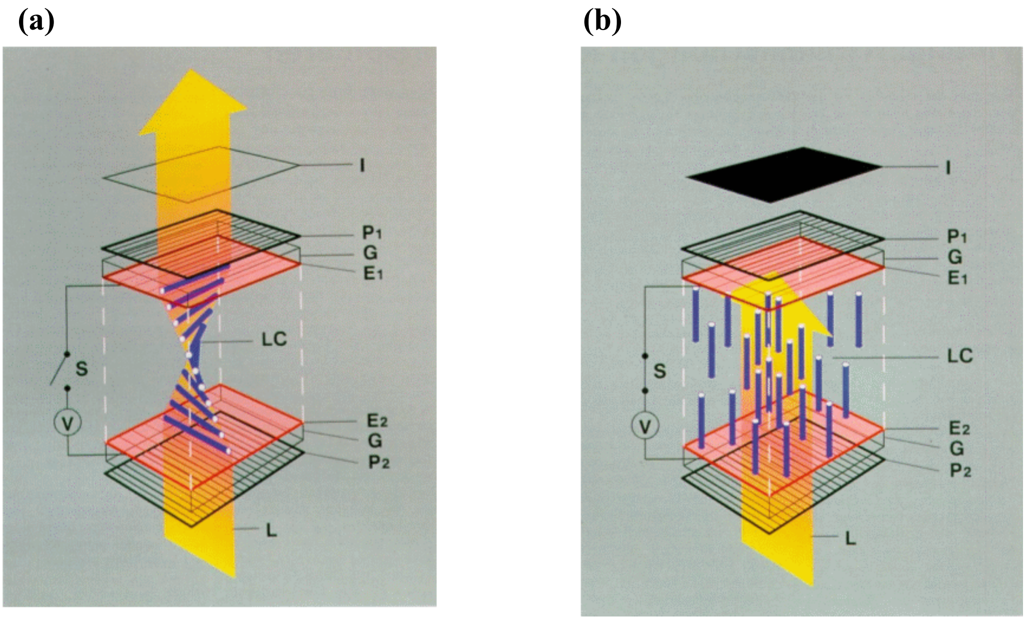


Fig 1.3.2.1 Principle of TN mode LC cell. (a) Without electric field, device show white state (b) With electric field, device show dark state

1.4 Active Plasmonics Materials

Various color filter can be realized to achieve spectral color by changing some geometry factors of the metal nanohole arrays structure and adding surrounding materials [23-27]. However, once fabricated with specific geometry conditions, the filtered light spectrum form is fixed. Therefore, this static structure is hard to be utilized as more useful applications. To give a dynamic characteristic to the hole arrays structure, there are two solutions. One is to use special materials having variable dielectric constant in order to utilize dielectric constant sensitivity of plasmonic structures. However, the amount of shift is small in visible range. Also it depends on the property of materials.

Other method is to use the polarization property of nanohole arrays structure. If the nanohole arrays are fabricated with asymmetric design, there are different resonance modes by polarization state of incident light. Therefore this fixed structure can emit various colors by change of polarization state of incident light [14] [28].

1.4.1 Liquid Crystal

The average direction of the LCs are known as the director and the refractive index of LCs is determined by director. Also, the director of LCs can be easily controlled by various methods such as electrical field, light, thermal energy, and acoustic wave. In addition, due to large birefringence, and low driving threshold, LCs are good candidate for active plasmonics. Above all, electric fields are the most attractive method to change the orientation of LC molecules. If an electric field is applied to LC molecules, it makes electric dipoles at both sides of a molecule. Then LC molecules try to match their orientation to the direction of the field. As using this mechanism, we can change the refractive index of LCs, then the condition of plasmonic resonance also changes [29-32].

Also, azobenzene is additional driving method as guest materials in LC molecules. As shown in the Fig 1.4.1.1, it can be transformed from trans-isomers to cis-isomers by photoirradiation. The isomerization will affect order of near LC molecules. Then, LC molecules are realigned to avoid transformation of azobenzene. As shown in the Fig 1.4.1.2, these change of director of LC molecules cause modulation of refractive index of LCs and the resonance point of plasmonic device changes [33, 34].

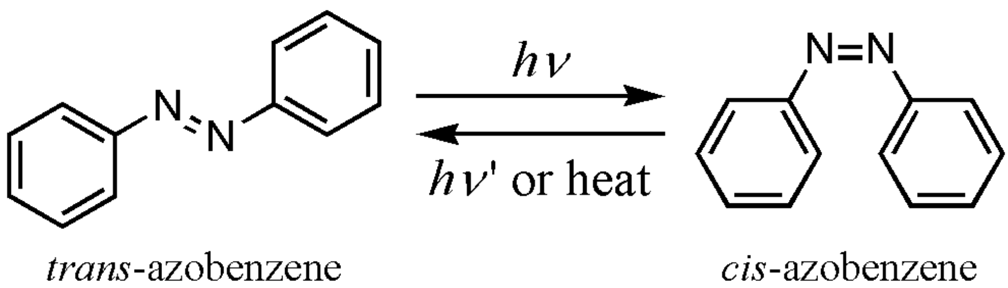


Fig 1.4.1.1 Azobenzene photoisomerization. The trans form (left) can be converted to the cis form(right) by external light. The cis form also return to the trans form by light or heat.

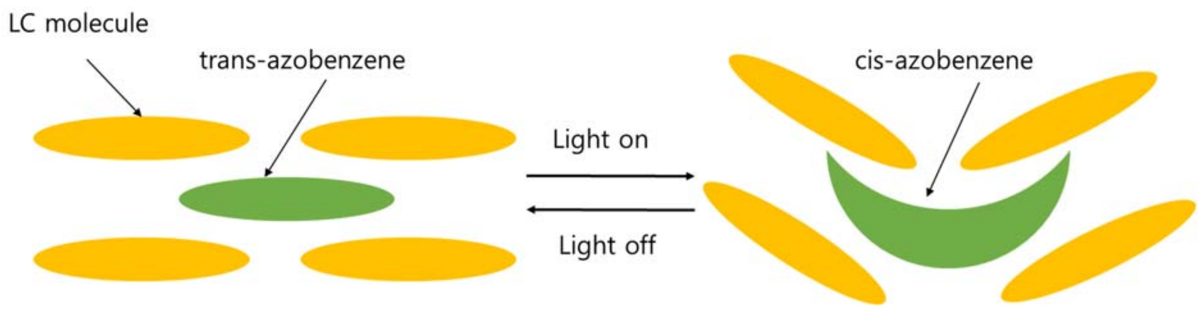


Fig 1.4.1.2 Dielectric constant tuning for active plasmonics using Azobenzene photoisomerization

1.4.2 Polymer

Another method to control the surrounding medium of a plasmonic device is to use of stimuli-responsive polymers. The polymeric chains of polymer are changed by pH, ionic strength and temperature. It makes transformation of refractive index of surrounding medium. For example, switching a conducting polymer electrochemically between its reduced and oxidized state can control the resonance condition of plasmonic structure. Several research groups demonstrates polymer switching device using PANI or PEDOT [35]. Also, other group demonstrates thermally induced active plasmonic device using poly(N-isopropylacrylamide) (PNIPAM) [36]. PNIPAM is changeable material from a hydrophilic state to a hydrophobic state by temperature. In addition, stress-responsive active plasmonic device is developed. They used plasmonic nanoparticles, and if mechanical stress is applied to the nanoparticles on polymer, they are separated and make shift of plasmonic band[37].

1.4.3 Photochromic Molecules

Plasmonic device can be modulated by surrounding photochromic molecules. Photochromic molecules exhibit optical switching property between transparent and absorbing sates. At each state, the spectra and the refractive index of photochromic molecules is changed, then plasmonic device become active device. Many researches [38, 39] are conducted to get switchable optical device using UV laser illumination. When device is illuminated by an UV laser, the state of photochromic dye is changed from transparent to absorbing state. And the spectra of plasmonic device changed. Reversible optical switching is also possible by turning off UV. These working principles can be used to optical switching component to treat optical circuit.

1.4.4 Inorganic materials

Vanadium dioxide (VO_2) is phase transition material between semiconductor and metal and it can be tuned by heat, light, or electricity, or mechanically. The semiconductor-to-metal phase transition (SMT) of VO_2 affects to entire refractive index of dielectric layer. Therefore, similar to other active material, plasmonic system with VO_2 also can modulate the resonance condition of plasmonic device [40, 41].

II. EXPERIMENT DETAILS

2.1 Concept of Active Plasmonic Color Filter

2.1.1 Design of Plasmonic Color Filter

In order to make accurate color filter, the polarization dependent color filter is researched. To get continuous color, we fabricate various type of color filter changing spacing design factor from 200nm to 400nm per 25nm. The diameter of hole is set to half of the shortest spacing between x and y direction. The thickness of Al film is fixed to 50nm and this thickness is enough to prevent tunneling transmission. The arrangement of hole arrays is quadrate shape having individual spacing for each x- and y-axes. This quadrangle design give color filter polarization dependent property.

2.2 Fabrication of Active Plasmonic Color Filter

2.2.1 Fabrication of Plasmonic Color Filter

In order to make color filter, a thin Al layer with a 70-nm thickness was deposited on a clean glass substrate using a thermal evaporator (KVE-T2000, Korea Vacuum Tech.). Then, periodic nanohole arrays are patterned using an electron beam lithography system (JEOL JBX-9300FS) with an accelerating voltage of 100 kV. Formed PMMA layer is used to etch mask for making hole at the Al layer. Al films were etched by an inductively coupled plasma and reactive ion etching (ICP-RIE) system. Fabrication step is described in Fig 2.2.1.1. As shown is Fig 2.2.1.2, fabricated color filter is measured by SEM and asymmetric hole arrays were made well on Al film.

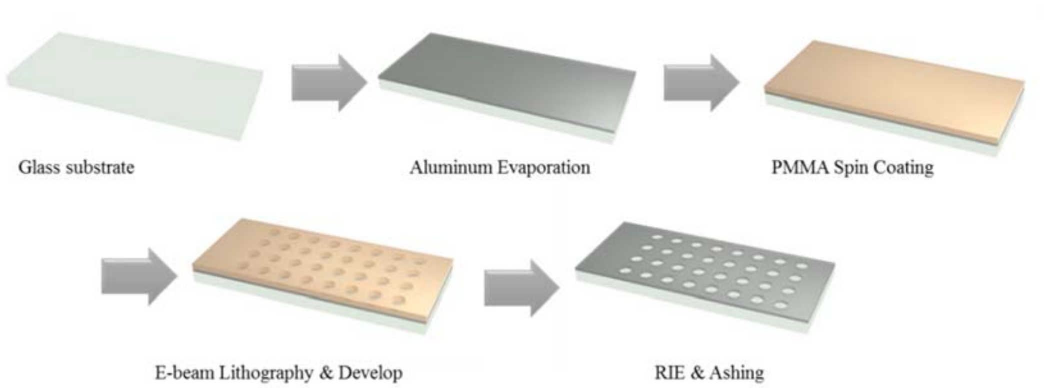


Fig 2.2.1.1 Schematic diagram of color filter fabrication process

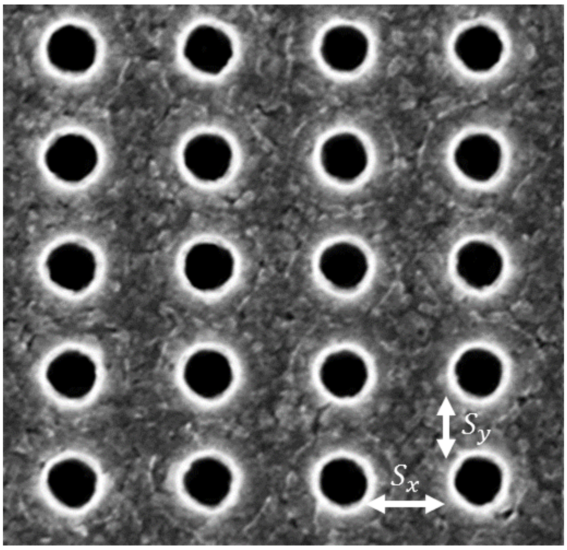


Fig 2.2.1.2 SEM image of nanohole arrays

2.2.2 Liquid Crystal Polarization Rotator

In order to make polarization optical rotator, we use twisted nematic(TN) mode of LC. We use commercial LC material (TL-203, Merck). First, the commercially available PI precursor (SE-7492, Nissan chemical) is spin coated on the indium-tin-oxide (ITO) coated glass. After the PI layer was baked at 80 °C for 10 min on a hot plate, the dried PI precursor film was thermally imidized at 250 °C for 1h. The thickness of coated layer is around 100nm. Then the PI layers were rubbed using a rayon velvet fabric and rubbing homemade machine. The alignment layer fixes the direction of LCs along mechanically rubbed direction. After rubbing step, silica spacer is used to suspend the gap between top and bottom layer. After fixing structure of LC cell, LC is injected to the gap of top and bottom layer. After sealing by UV glue, LC cell is completed.

In addition, another LC working mode, IPS (In Plane Switching), is studied to figure out further useful applications by horizontally tilting linear polarization state. To easily get well aligned state of LC, modified new working mode which has transition of LC formation from IPS to TN-lateral working mode.

Fabrication step is not far previous TN mode fabrication. But the difference is additional electrodes array of top layer, which can give lateral electric field in the LC cell. First, electrodes are patterned to ITO coated glass using photo lithography. Then ITO layer is etched by ITO etchant. Fig 2.2.2.1a shows the micro optical photography of ITO electrodes. As shown in Fig 2.2.2.1b, the width of electrode is 80μm and the spacing between each electrode is 120 μm. After fabrication of top ITO electrode arrays layer, some process to make LC cell proceed from previous fabrication step. The important consideration point in the fabrication process is the direction of rubbed state at the top alignment layer. At the top electrodes layer, LC can be tilted by formed electrodes arrays. However, if the direction of LC is perpendicularly arranged to electrode at the rubbing process, the direction of LC is not changed regardless of electric field. Therefore, the rubbing direction of top alignment layer is set to parallel direction of ITO electrodes.

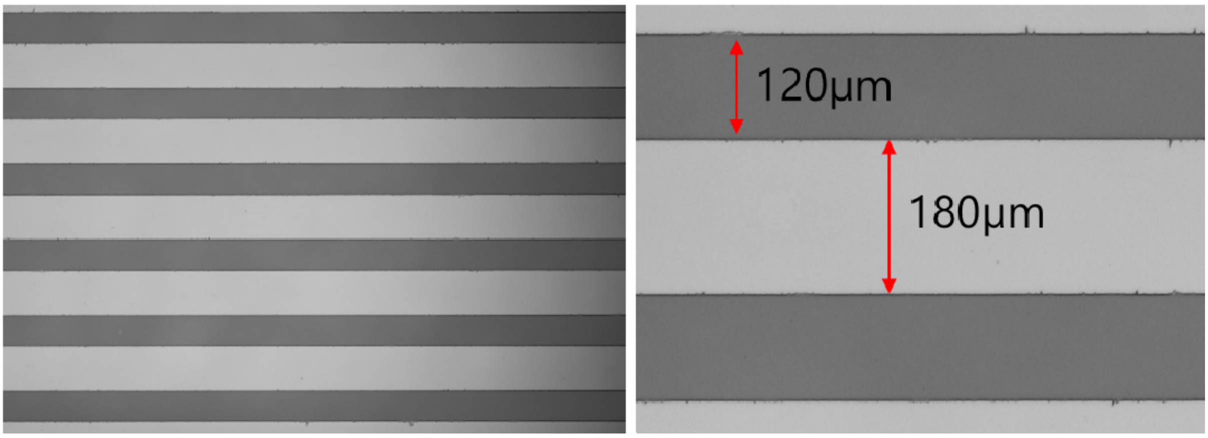


Fig 2.2.2.1 Micro-optical image of ITO electrodes arrays

2.2.3 Active Color Filter with Changeable Dielectric Constant

Plasmonic color filter and LC are combined to investigate the effect of the refractive index of liquid crystal. To maximize the change of the refractive index of LC, alignment layer at the bottom surface is eliminated. According to other research [42], many low loss plasmonic metals such as silver show homeotropic alignment due to their surface energy. Our Al film has appropriate surface anchoring energy to horizontally align LC at the surface of Al film. Also aluminum is a proper material to avoid visible domain absorption. The thickness of LC cell is enough to prevent the effect of vertical plasmonic wave, top layer is coated with alignment layer.

Polymer dispersed liquid crystal (PDLC) and LC is used to dielectric variable materials. PDLC has their own optical shutter property by transition from opaque to transparent state. The difference of refractive index between polymer and LC can be controlled by electric field and PDLC device can be used to optical shutter. The optimal composition of PDLC is 80, 20wt% for LC and polymer, respectively. And this condition is selected to achieve good optical shutter effect [43].

2.2.4 Active Color Filter with Polarization Effect

After making TN cell, we combined TN cell to plasmonic color filter that has various colors resonance mode with different polarization. We use previous fabrication step of TN cell. As shown in the Fig 2.1.2.1, the simulated electric field distribution at the surface of the plasmonic color filter is almost same with the case of flat surface. Therefore plasmonic color fitler can be used to bottom electrode layer. This gives advantage in fabrication step because it doesn't need additional electrode layer to give electrical field.

Fig 2.2.4.1 shows a schematic diagram of our device. First, unpolarized incident light is converted to y polarized light when it passes y polarization film. Next some y polarized light become x polarized light by TN shape LC. This x polarized light meets plasmonic color filter. Then, this light couple to nanostructure with only x direction. Therefore, with structure property of x direction, color filter shows red color.

However, other y polarized light is not affected by vertical shape LC because of birefringence property of LC. The direction of LC is aligned to electric field with vertical direction. Passed light can couple to only y direction of nanostructure. Then, it shows green color. In conclusion, these y and x polarized light has individual plasmonic resonance modes at the surface of color filter because of its different geometry of hole arrays. Due to optoelectronic effect of LC, the direction of LC can be easily tuned and it switches the polarization effect. Therefore, just applying electric field to our device, we can make tunable color filter.

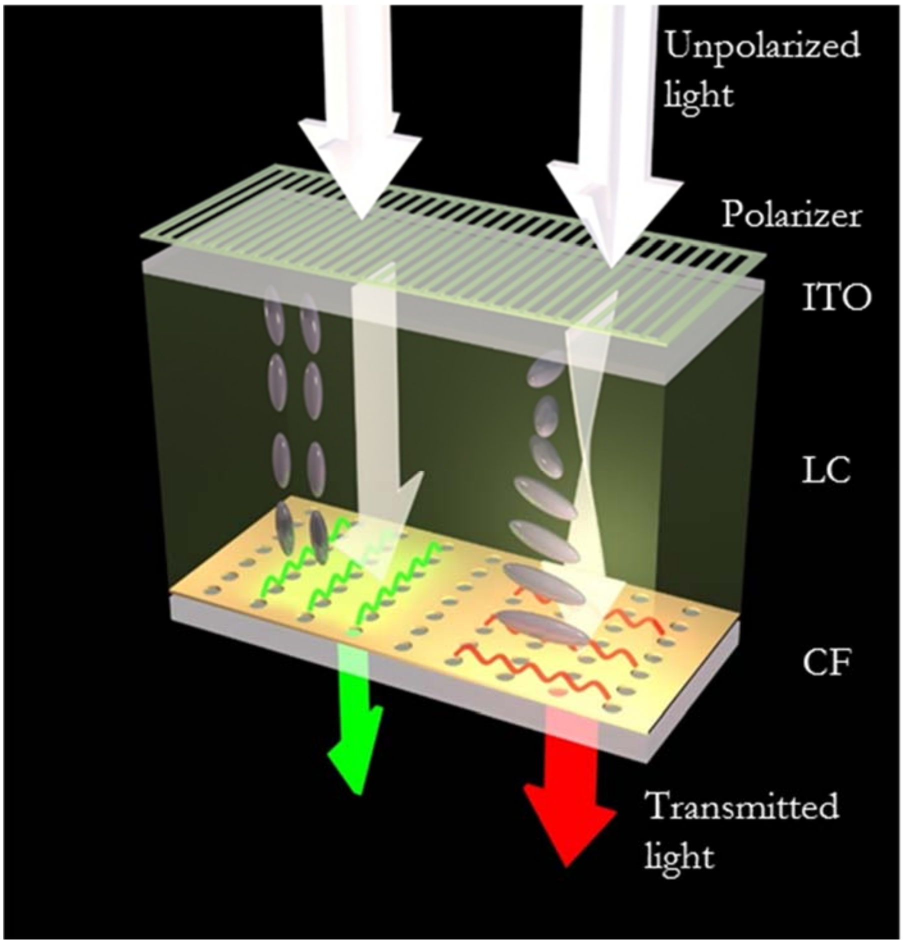


Fig 2.2.4.1 Schematic representation of electrically tunable multi-color device

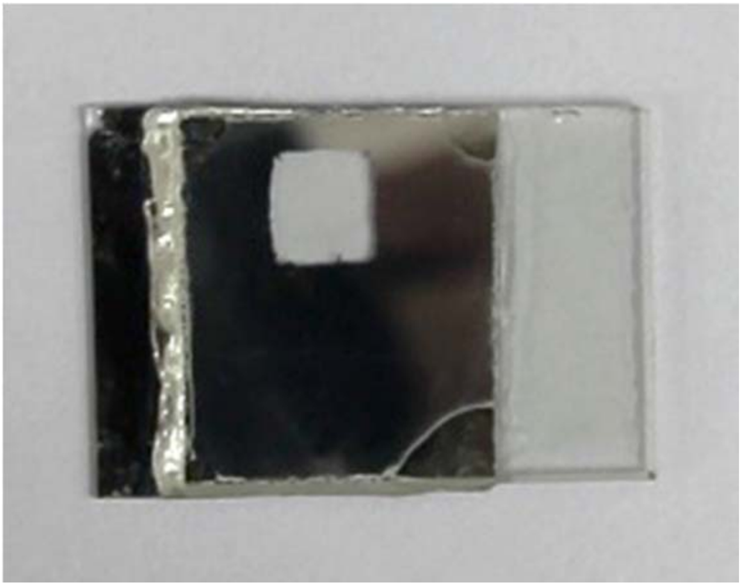


Fig 2.2.4.2 Image of fabricated active color filter

2.3 Measurement System for Fabricated Color Filter

The transmission spectral properties of the fabricated plasmonic color filter were measured with a CCD based spectrometer (DALSA PRO-5200) which had an available wavelength between 400 nm and 780 nm with a 1 nm resolution. The light source was set vertical to the filters when the spectral measurements were performed. Optical micro-photograph image is taken by CCD image sensor.

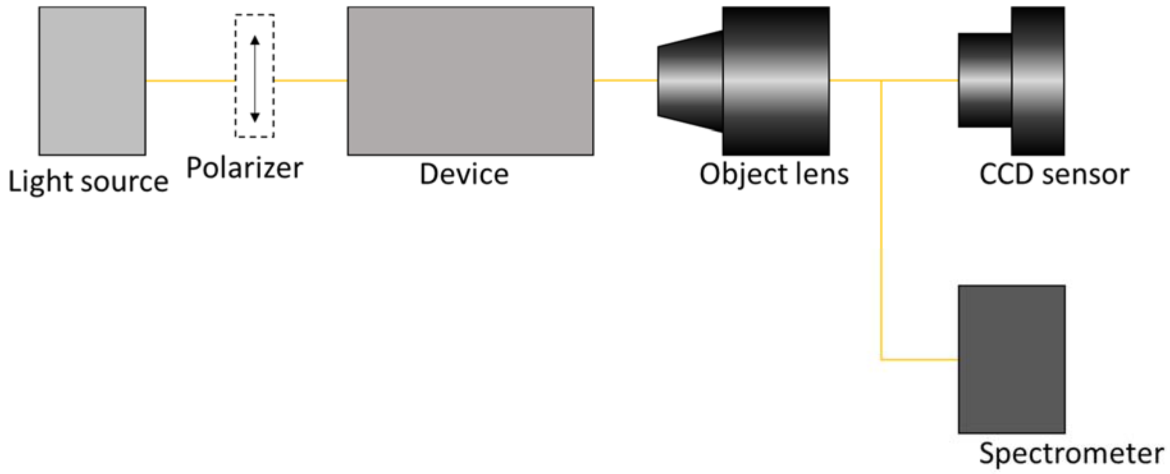


Fig 2.3.1 Measurement system for fabricated color filter

III. RESULTS AND DISCUSSION

3.1 Theoretical Studies for Nanohole Array Structure

3.1.1 Simulation of Electric Field at the Surface of Metal

In order to utilize metal film to electrode, the distribution of electric field of metal surface is simulated using COMSOL. As shown in the Fig 3.1.1.1, electric field becomes vertical direction in the case of flat metal electrode. However, considering geometric effect of hole, the electric field distribution around hole is deformed (Fig 3.1.1.1). Especially, electric field lies horizontally inside hole. It makes inaccurate experiment result in refractive index sensitive color filter. However, it can be not important point at the case of polarization rotator cell. Because, after fabrication of polarization rotator, the alignment layer will cover nano-hole structure and LC cannot be placed in hole area. Therefore, LCs on the alignment layer will not be affected by those strange electric field.

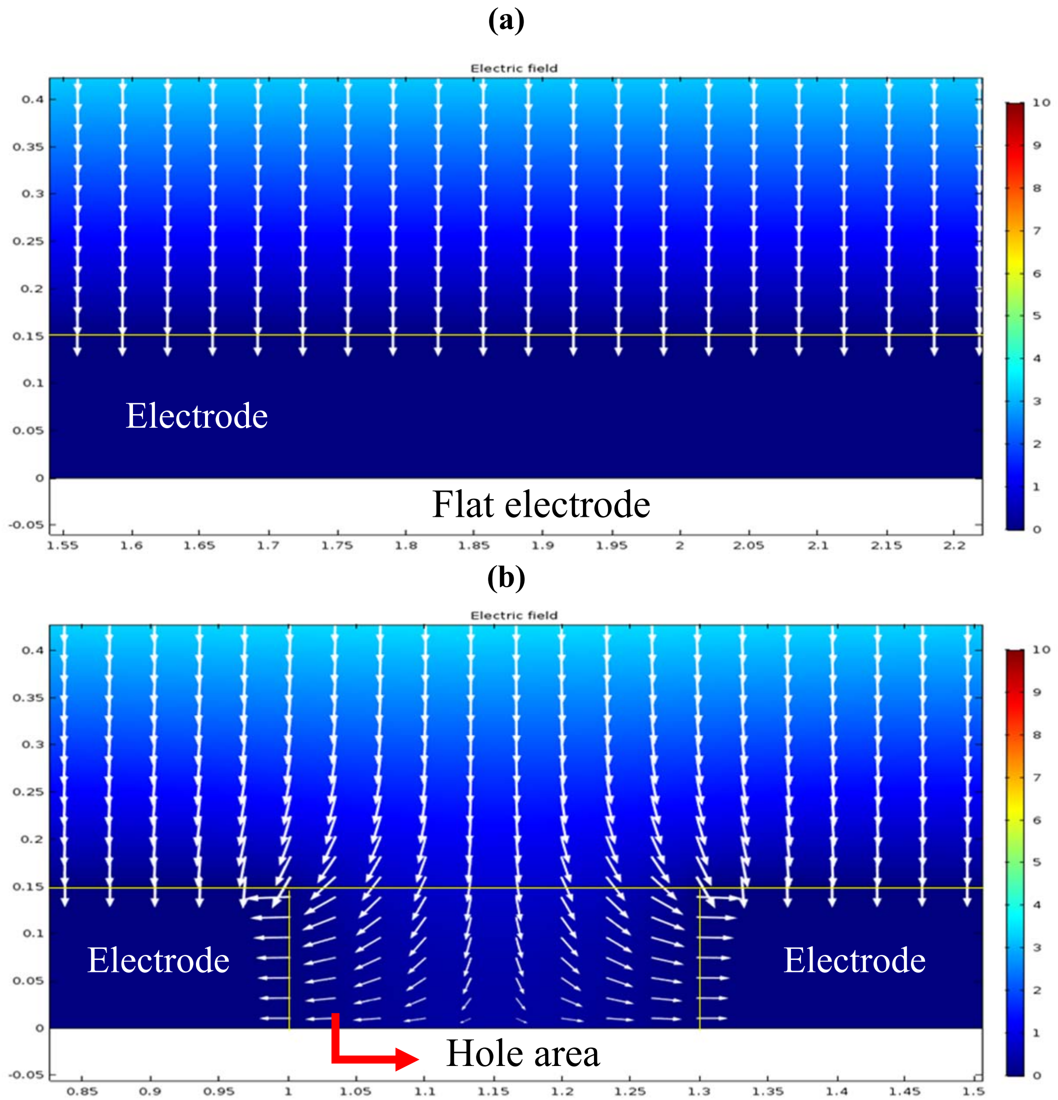


Fig 3.1.1.1 Simulation of electric field distribution at the surface of metal film (a) electric field simulation at flat surface (b) electric field simulation around nanohole structure

3.1.2 Electric Field Intensity Distributions for the Asymmetric Nanohole Arrays System

Before assembling LC polarized switch structure to plsmonic color filter, the optical characteristics of plasmonic color filter were studied. As shown in the Fig 3.1.2.1, simulated electric field intensity distributions are presented depending on polarized angle of light. Coupled plasmonic mode only appears with the direction of incident polarized light. If x polarized light pass the nanohole arrays, it only interacts with structure of x direction. Otherwise, when y polarized light come to fabricated structure, it only couples with the structure of y direction. Therefore, asymmetrically aligned structure make several modes based on different spacing between each hole.

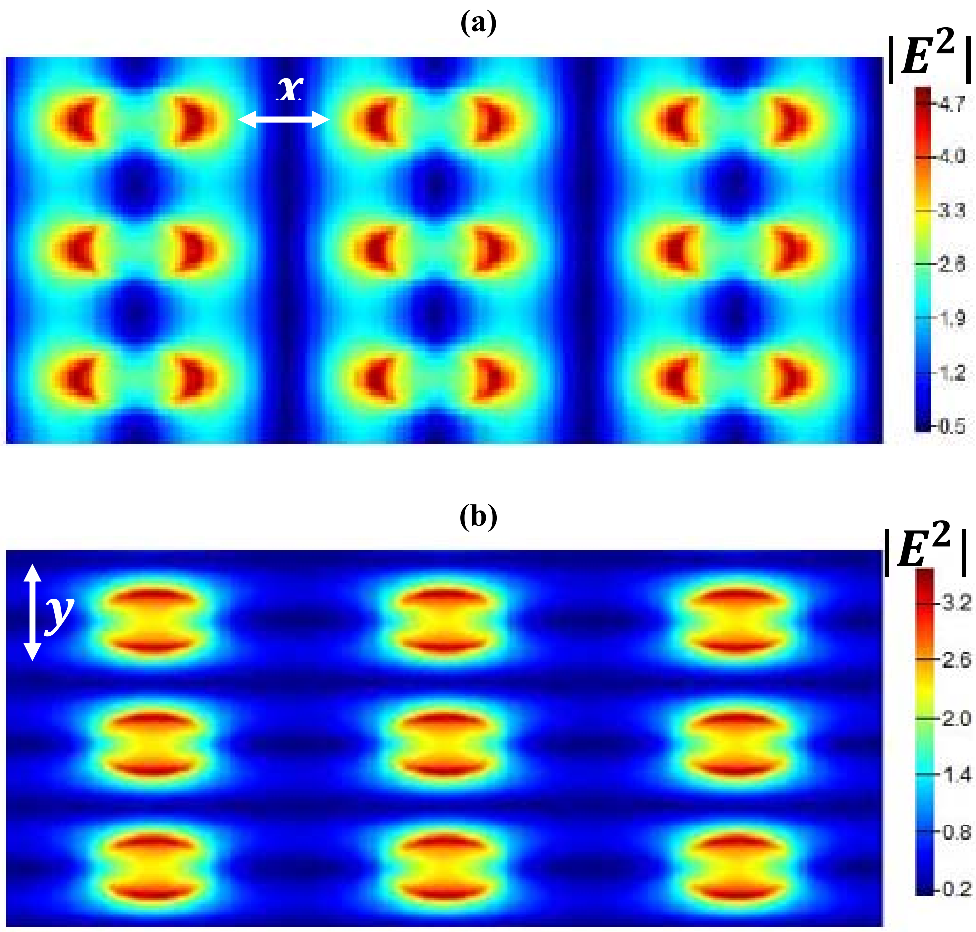


Fig 3.1.2.1 (a-b) Electric field intensity distributions calculated at the corresponding transmission resonances for the asymmetric nanohole arrays system on (a) x polarized incident light and (b) y polarized incident light.

3.1.3 Simulation of Electric Field at the ITO Electrodes Array

In order to figure out the intensity and direction of electric field, two electrodes structure is simulated. One electrode is applied by 10V and another electrode is ground state. Between two electrodes, electric field intensity is linearly changed. The direction of electric field is important because when LC layer is fabricated inside LC cell, LC is horizontally tilted at the only small area having horizontal electric field. In Fig 3.1.3.1, the area which is around half of the spacing between two electrodes is enough to sustain horizontal electric field. Fabricated color filter size is 50μm and 120μm spacing is selected to use horizontal electric field considering margin of error.

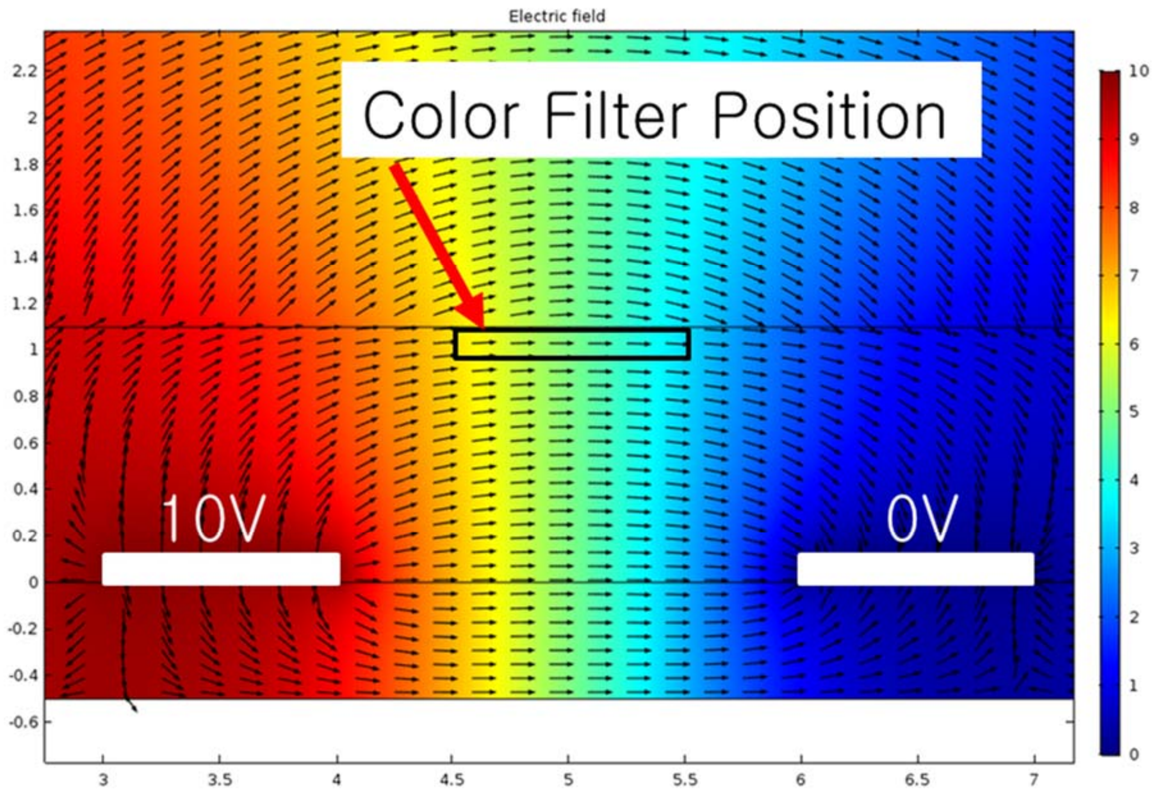


Fig 3.1.3.1 Simulation of electric field distribution at the ITO electrode array (a) electric field simulation at flat surface (b) electric field simulation around nanohole structure

3.2 Characteristics of Plasmonic Color Filter

Fig 3.2.1 shows the optical micro-photograph and measured transmission spectra of symmetric design for unpolarized incident light. Increasing spacing factor makes the red shift of spectra. The relation between spacing and the position of peak wavelength is revealed in the equation 2. Also, various colors appear with different spacing of nano-hole arrays. However, the transmittances are not high. It mainly due to the asymmetric effect of dielectric constant between upper air layer and bottom glass layer [44]. If the light incidence condition is the same of emission condition, high transmissive yield can be achieved. But, it is not a serious problem. Considering the combination of LC to color filter, we deliberately eliminate any index matching layer on the top layer. Actually, after combination LC to color filter, this poor spectrum is improved. And the details are discussed more in the latter.

The color filter shows different colors in 0° and 90° polarization state of the incident light (Fig 3.2.2). If we change specific spacing factor, we can get various colors from blue to red in one design.

Fig 3.2.3 shows one representative results of specific color filters (x spacing =325nm, y spacing 225nm). It showed two different color states, blue and green color, with different polarization state. Simply changing polarization state of incident light induces the different color states.

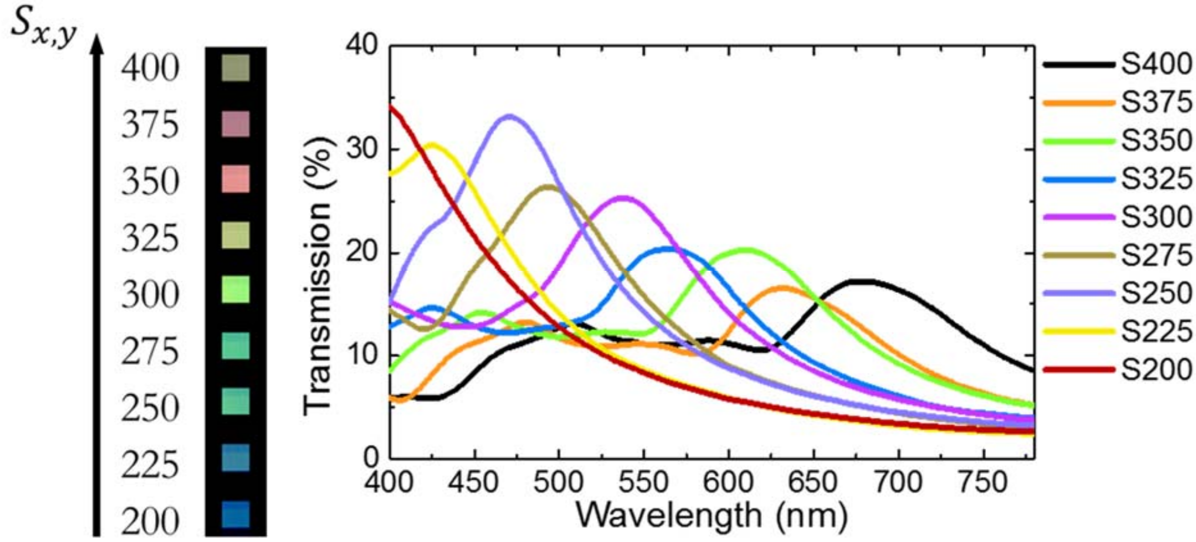


Fig 3.2.1 Optical micro-photograph and measured transmission spectra of symmetric design for unpolarized incident light

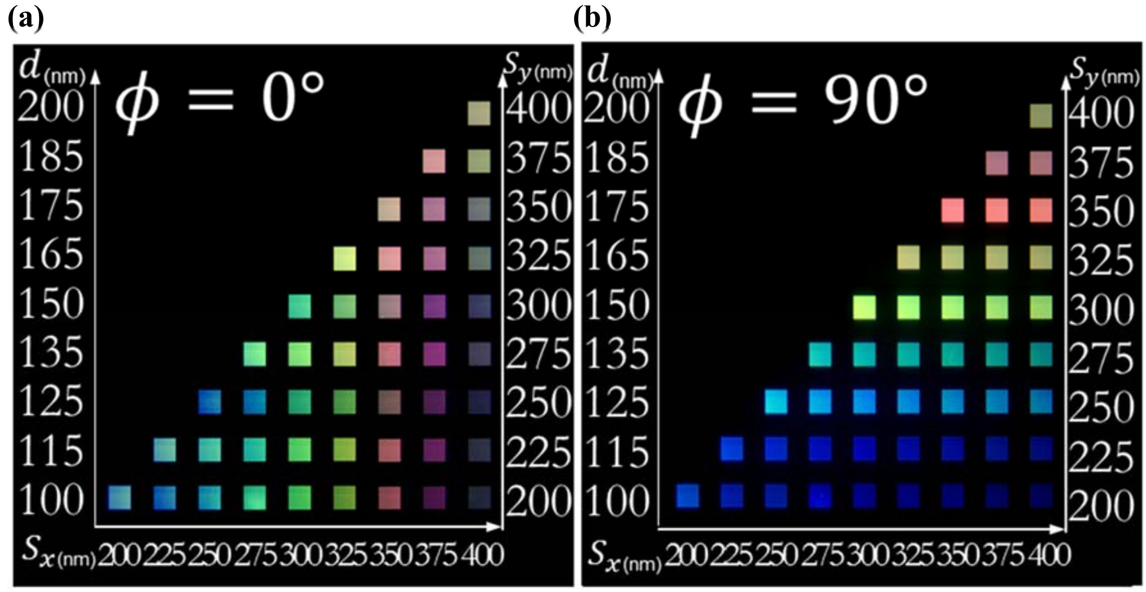


Fig 3.2.2 Optical micro-photograph of multi-color filter for 0°(a), and 90°(b) polarization of incident light

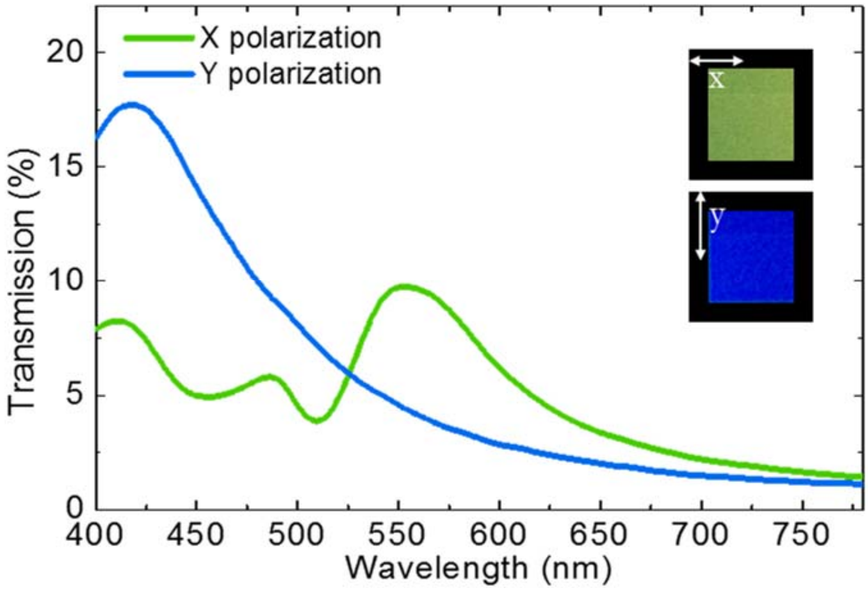


Fig 3.2.3 Optical micro-photograph and measured transmission spectra of specific design of $S_x = 325$nm, $S_y = 225$nm.

3.3 Characteristics of Liquid Crystal Polarization Rotator

To assemble LC polarizer switch structure, the optical effect of LC alignment layer was investigated. Fig 3.3.1 shows the polarization test of TN cell in crossed polarizer and analyzer. Two linear polarizers are located at top and bottom sides. In the OFF state with no electrical field, TN cell shows white state owing to its polarization effect (a). In the ON state with electrical field, LCs tend to align along electric field, then TN cell lost its polarization effect. Therefore, TN cell shows dark state (b). The ON-OFF property of TN cell is investigated in the Fig 3.3.2. The brightness changes from 100% to 25% when electric field is applied. Transmission is saturated to 25%. Although imperfect TN shape with our insufficient equipment, it shows polarization effect. In addition, the threshold voltage is around 4V, so that the TN cell design can be applied easily to various electrical device concepts.

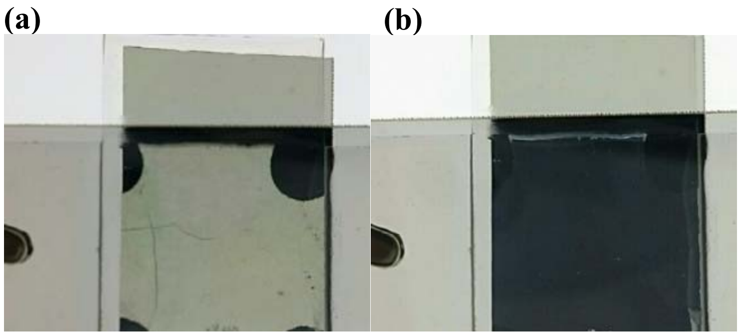


Fig 3.3.1 Polarization test of TN cell with crossed analyzer and polarizer at the OFF state (a) and ON state (b)

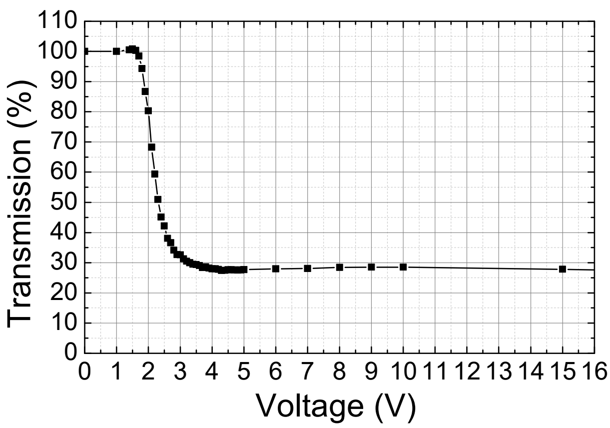


Fig 3.3.2 On-off property of TN mode. Spectrum is measured in crossed analyzer and polarizer

In addition, another LC working mode, IPS to lateral working mode, is studied. After fabrication of complete LC cell, polarization test and ON-OFF ratio are measured. Two linear polarizers is stacked with orthogonal direction on and under LC cell. With only two stacked polarizers, light is prevented output polarizer and dark color is presented. However, with our LC cell, output color is changeable. Fig 3.3.3 shows the polarization test of new cell in crossed polarizer and analyzer. Between neighboring electrodes, the direction of LC is tilted by formation of electric field, orthogonal to electrode direction. In the OFF state with no electrical field, this cell shows white state owing to TN polarization effect (a). However, in the ON state with electrical field, dark region appears between patterned electrodes because lateral electronic field make horizontal direction of LC. Then LC cell lost no polarization effect (b).

To exactly study performance of polarization rotator, ON-OFF property of TN-lateral cell is investigated in the Fig 3.3.4. However, it needs high voltage to make sufficient electric field to tilt LC. The reason is that spacing between each electrode is 120μm and this spacing is 24 times of the gap between top and bottom layer of TN cell. Therefore, 270V is not enough to saturate rotation of LC. The brightness of two working states changes from 100% to 25% and it is worth to be used for polarization rotator, although it shows not perfect polarization changing.

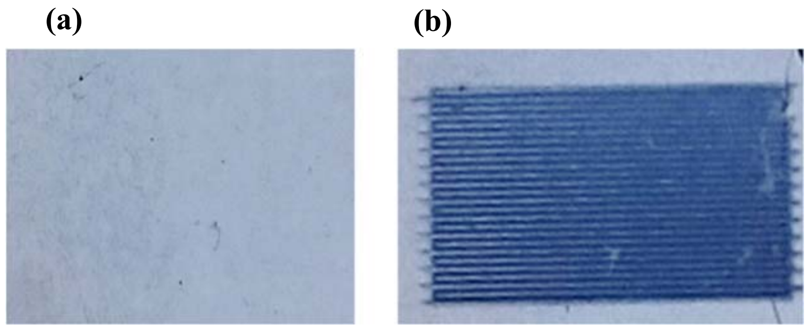


Fig 3.3.3 Polarization test of TN- lateral cell with crossed analyzer and polarizer at the OFF state (a) and ON state (b)

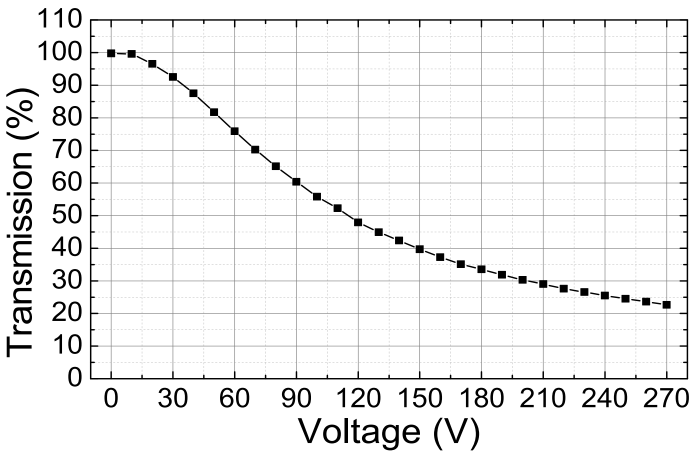


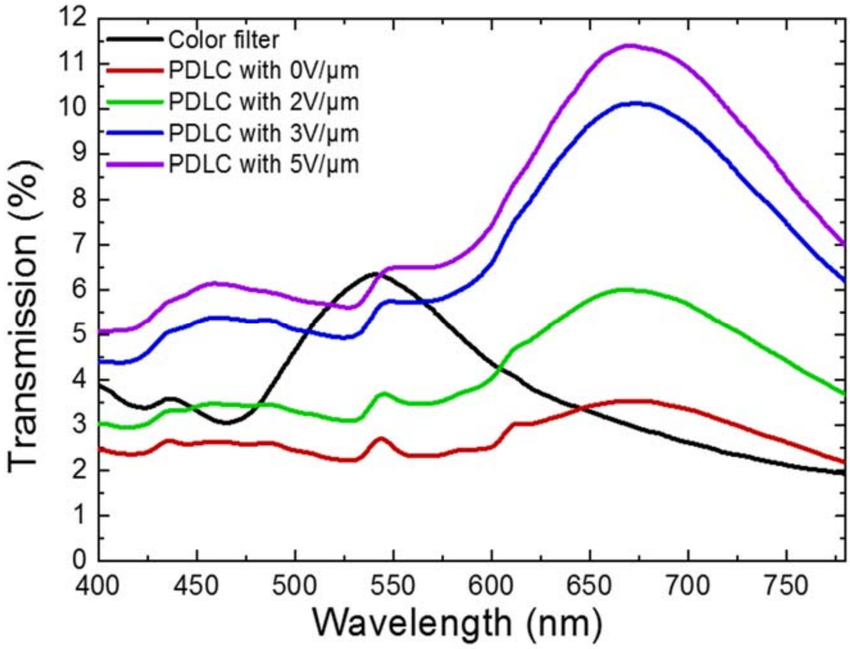
Fig 3.3.4 On-off property of TN-lateral mode. Spectrum is measured in crossed analyzer and polarizer

3.4 Characteristics of Active Color Filter with Changeable Dielectric

To study only the effect of dielectric constant, PDLC or LC is combined to plasmonic color filter. It has remarkable advantage that the position of peak can be tuned to continuously by electric field. If we don't choose refractive index modulating method and make asymmetric nanostructure, it can show only two fixed position of transmission peak with different polarization of incident light. Therefore, it only shows the color with combination of two peaks. However, dielectric constant based method can continuously change the position of transmission peak.

As shown in the Fig 3.4.1, the position of peak is changed by applied electric field. This PDLC shows small red shift, around 8nm. Because PDLC is composition of polymer and LC and only LC is changeable material. Our LC has a n_e and n_o of 1.73 and 1.53, respectively. The maximum birefringence are 0.2 and the arrangement of LC in the polymer cell is randomly arranged. Therefore, entire change of refractive index is small and it shows small amount of wavelength shifts.

(a)



(b)

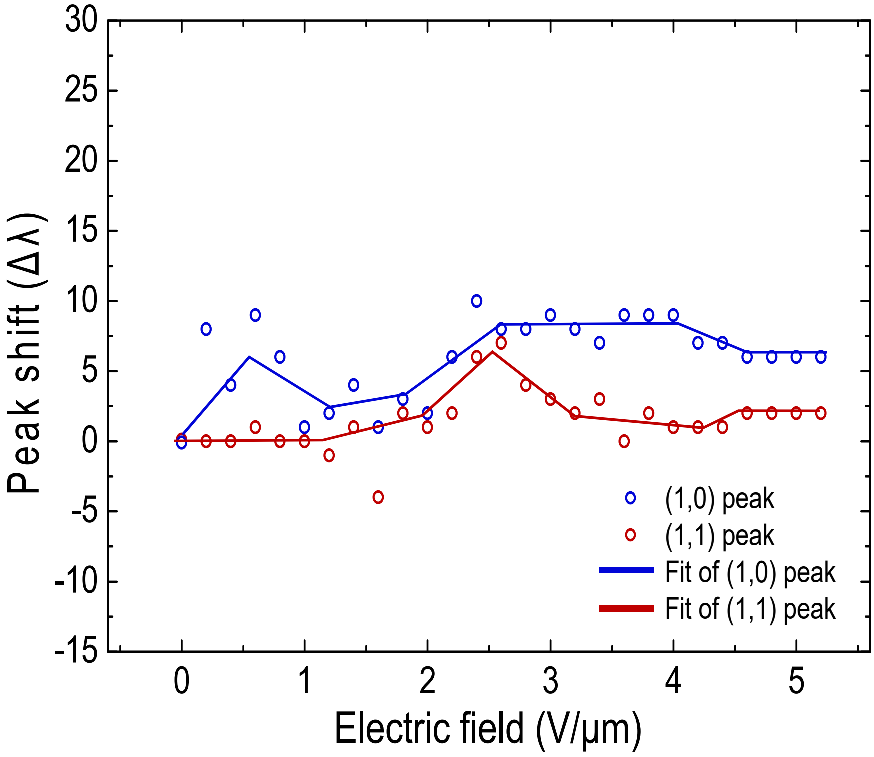


Fig 3.4.1 (a) Measured transmission spectra of the nanohole arrays with PDLC in different electric field. Before adding PDLC, initial position of peak is 541nm. (b) The position of peaks shifts from 457 to 459nm at small peak, and from 665 to 671nm at large peak. The design of nanohole arrays is s=360nm, d=180nm.

Furthermore, the effect of birefringence of LC is investigated using only LC. First, with alignment layer, the amount of wavelength shift is small. Then we don't use alignment layer to increase the depth of contacting area at the interface between dielectric and metal layer. Although all LC are not aligned to same direction, almost LCs at the surface becomes horizontal direction. Working process of device is presented in Fig 3.4.2.

When LC layer is added to plasmonic color filter, it makes large red shift because the air layer is changed to LC layer having high dielectric constant. When LC aligns to vertical direction along electric field, the position of wavelength peak is red-shifted. As shown in the Fig 3.4.3, the position of wavelength peak is evidently red-shifted. It shows 13nm shift at the saturation region.

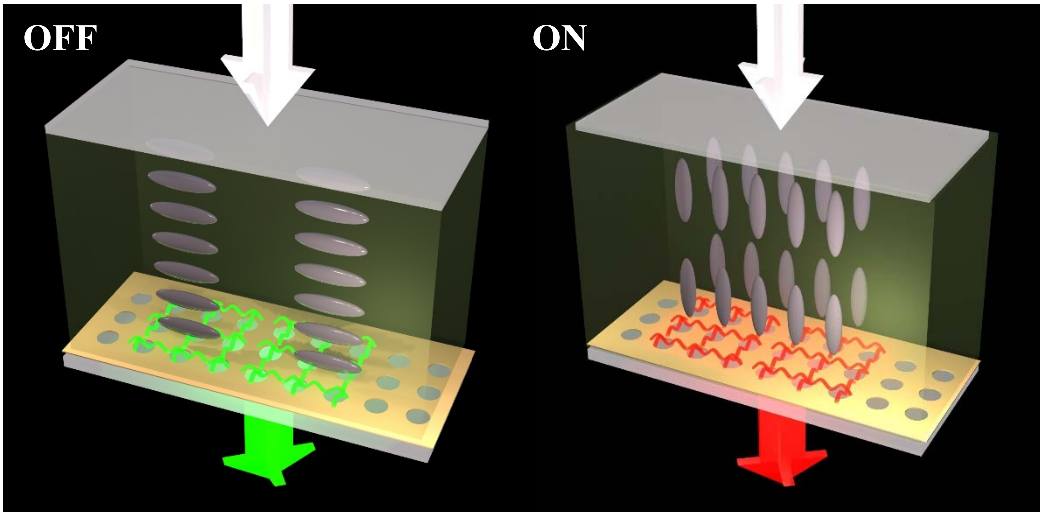
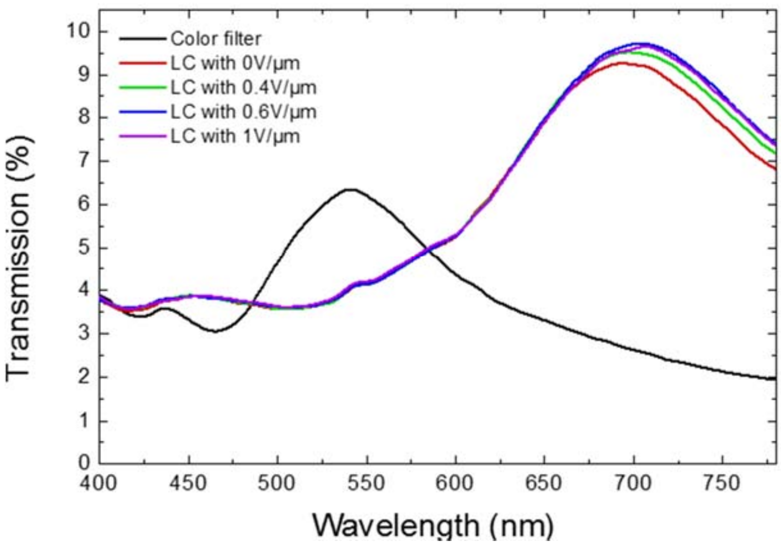


Fig 3.4.2 Plasmonic color filter tuning the refractive index of LC

(a)



(b)

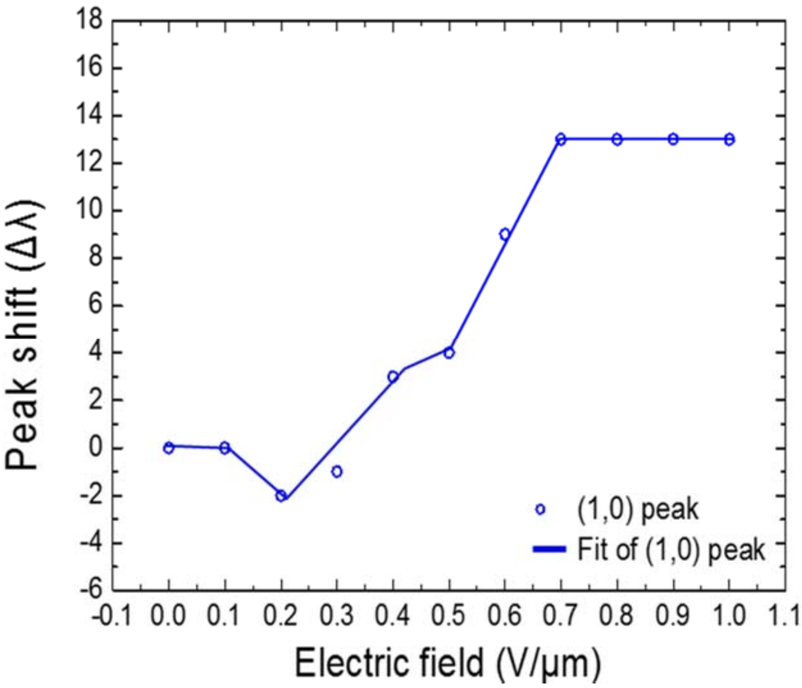


Fig 3.4.3 (a) Measured transmission spectra of the nanohole arrays with LC in two different electric field. (b) The position of peaks shifts from 669 to 685nm. The design of nanohole arrays is s=360nm, d=160nm.

To analyze the shift of wavelength peak, the comprehensive understanding about LC and surface plasmon is necessary. Surface plasmon wave has both lateral and vertical electronic wave [2]. In the dielectric layer, the effect of vertical direction of electronic wave is larger than lateral direction of electronic wave and coupled resonance mode is more sensitive to vertical direction of refractive index variation [32] . Therefore, in contrast with classical property of LC, vertical direction of LC has large refractive index and lateral direction of LC has small refractive index. Therefore, this vertical alignment of LC makes redshift. The amount of shift can be increased with high birefringence LC [19]. If another LC having high birefringence is used to our device, the amount of shift can be improved.

3.5 Characteristics of Active Color Filter with Polarization Effect

3.5.1 Plasmonic Color Filter on TN Polarization Rotator

Before combining LC to plasmonic color filter, we just put polarization rotator on the plasmonic color filter. Polarization rotator and plasmonic color filter is divided by air gap between two components, therefore the change of dielectric constant of LC cannot affect to plasmonic resonance property. And just polarization modulation can be tuned by electric field. Asymmetric plasmonic color filter is prepared to investigate polarization dependent property. As shown in the Fig 3.5.1.1, we fabricated "DGIST" letter, with nanohole arrays having diverse design factor at 0° and 90° direction. At the different polarization state of incident light, the color of letter change. In order to operate color system, we give electric field to the TN LC cell. For measurement system, we put y polarization film at the incident side. Unpolarized light passes the polarization film then it becomes y polarized light. As shown in the Fig 3.5.1.2, the color of letter is changed with the change of polarization state of incident light. At the off state, y polarized light meet TN alignment LC, and light tend to become x polarization state. These x polarized light pass color filter, then it only couples the structure at x direction and show the color of x direction structure. However, at the on state, y polarized light is not affected by TN LC cell because vertical alignment of LC cannot give polarization effect. Then these y polarized light pass color filter with y direction. That is, the color of structure having x direction appear.

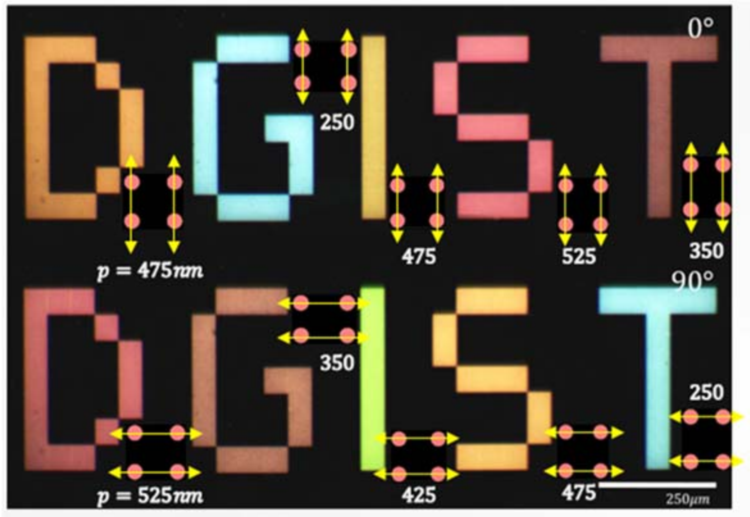


Fig 3.5.1.1 Design of asymmetric color filter

(a) (b)

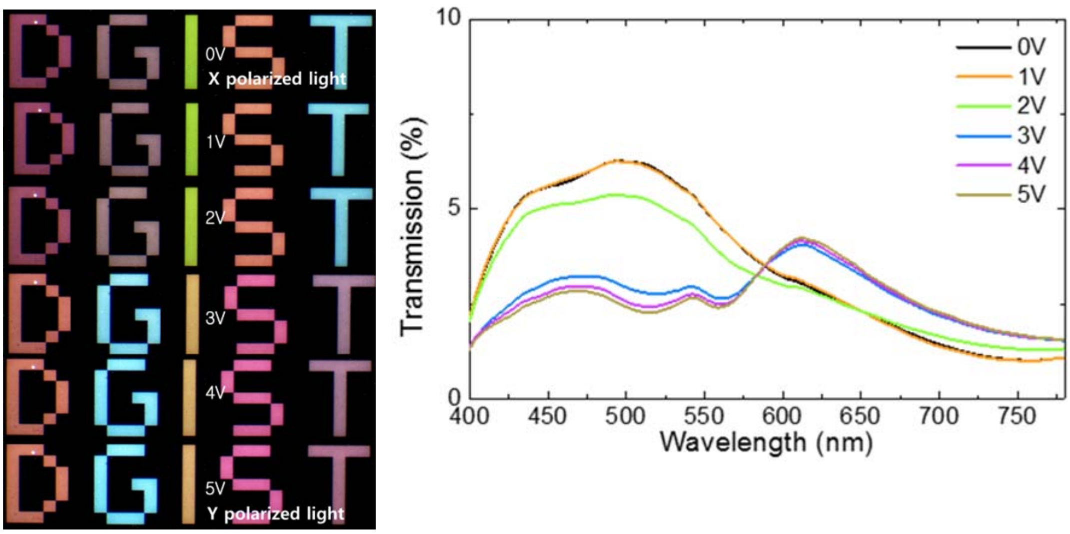


Fig 3.5.1.2 (a) Color of “DGIST” with different electric field. (b) Optical micro-photograph and measured transmission spectra of “T”

3.5.2 Plasmonic Color Filter on TN-Lateral Polarization Rotator

After testing of TN working mode, availability of another mode is studied. Without complete combined structure, fabricated plasmonic color filter and TN-lateral polarization rotator are used to be aware of the possibility of lateral tilting working. To supply linear incident light, a linear polarizer is used at the bottom of color filter and LC cell. As previously introduced high working voltage, polarization rotator needs high voltage to tilt LC and 270V is not enough to perfectly tilt LC. However, enough tendency of color transition is observed. At the OFF state, y polarized incident light is transformed to x polarized light. These x polarized lights pass nanohole arrays of plasmonic color filter with x direction and it is filtered to red color. (Fig 3.5.2.1a). However, at the ON state, LC is aligned along to horizontal electric field and LC cell lost its polarization effect. Therefore, when y polarized light pass LC cell, it is not affected and pass nanohole arrays with y direction (Fig 3.5.2.1b).

As shown in the Fig 3.5.2.2, the output color of color filter is transformed from orange to blue and Fig 3.5.2.3 shows color transition from deep orange to yellowish green. Some fluctuation at the strong electric field may come from cell gap effect of LC cell. CIE chromaticity diagram shows its color distribution and it shows almost linear shape. The advantage of this formation of LC cell is use of linearly tilted polarization state of incident light. At the end of this thesis, combined structure having TN mode LC and color filter is researched. However, as shown in the Fig 3.5.4.4, CIE chromaticity diagram shows not linear transition of color because TN mode cannot make linear polarization state between 0 and saturation voltage. Between ON and OFF mode, TN cell has circular polarization mode and it is not easy to be predicted. Therefore, output color cannot be exactly designed. However, in the TN-to lateral mode, the polarization state of LC cell is linearly changed and this transition cause predictable result at the combination of orthogonal linear polarization.

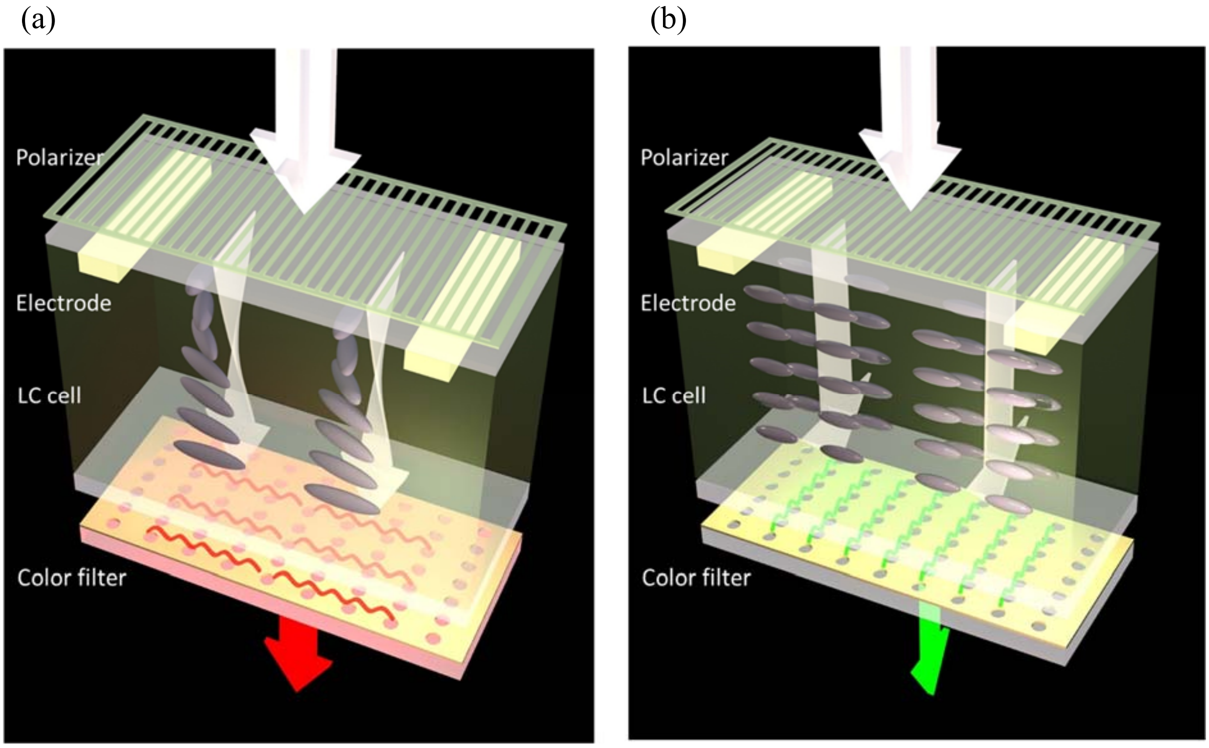


Fig 3.5.2.1 Plasmonic color filter tuning by TN-Lateral LC mode at the OFF state (a) and ON state (b).

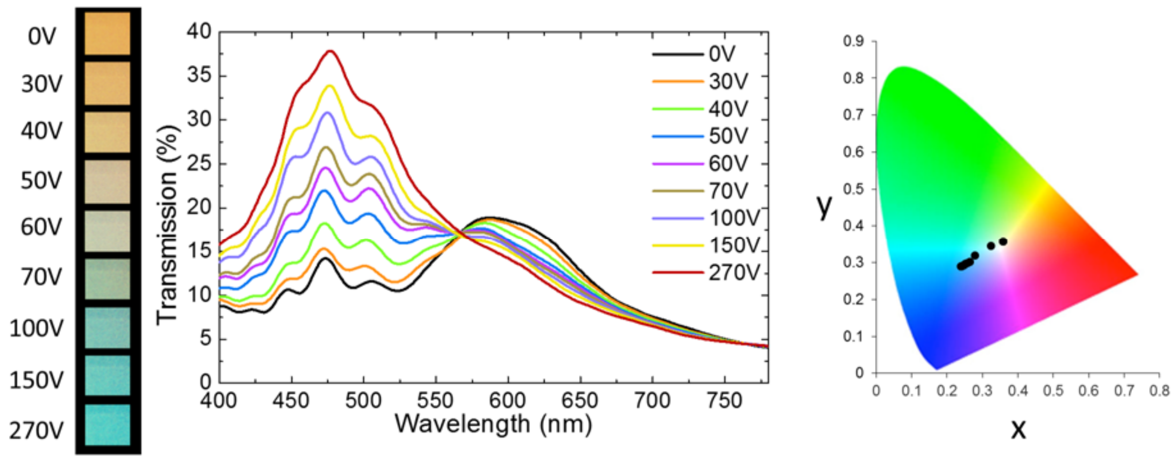


Fig 3.5.2.2 Optical micro-photograph, measured spectra and CIE chromaticity diagram of (a) $S_x = 325\text{nm},\ S_y = 225$

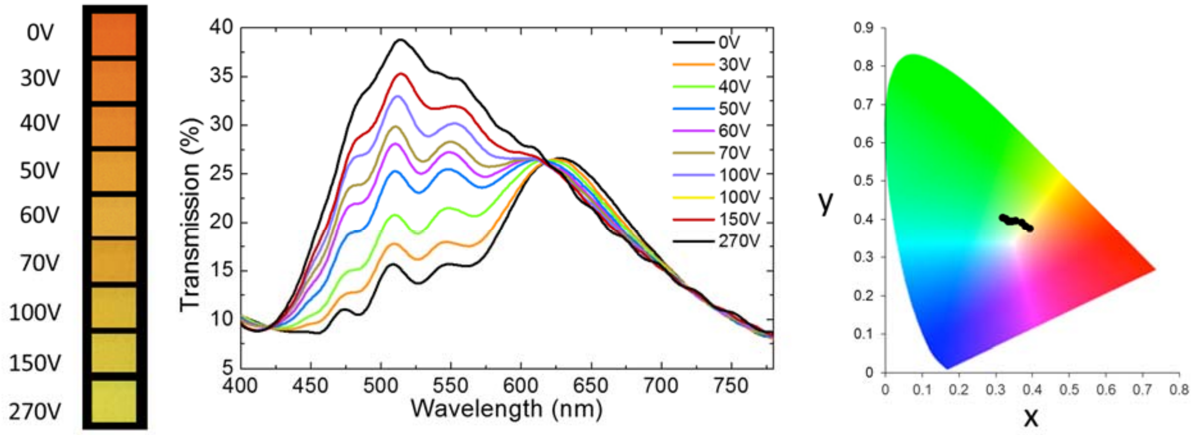


Fig 3.5.2.3 Optical micro-photograph, measured spectra and CIE chromaticity diagram of (a) $S_x = 350nm,\ S_y = 275$

3.5.3 The Effect of Alignment Layer to Color Filter

To assemble LC polarizer switch structure, the optical effect of LC alignment layer was investigated. Because the alignment layer make additional shift of wavelength peak by its high refractive index. The polyimide (PI) type of LC aliment layer (SE-5811, Nissan chemical) was formed on nanohole array structure using spin coating and drying step. Due to its different refractive index, 1.62, from that of air, some optical characteristics were changed and the new conditions were optimized for a good multi-color tuning system. As shown in Fig 3.5.3.1, due to the changing optical characteristics of surrounding material, PI LC alignment layer, the plasmonics resonance peaks shift to larger wavelength, although the geometric design factors of nanohole array are unchanged. It is shown that the relationship changes to $\lambda_{peak} \approx 2.11S$.

For 225nm spacing condition, the resonance peak shift from 425nm to 512nm by PI coating (Fig 3.5.3.2). Because of higher refractive index of PI alignment layer, all resonance peaks move to longer wavelength. Therefore, when LC witch system assembles to the nanohole color filter structure, smaller spacing is required between holes below 200nm to get blue color. Higher refractive index of PI layer makes a desirable result for transmittance. As mentioned previously a little, incident light induces plasmonic oscillation between the surface of glass and the Al metal film. However, since light re-emission is produced from the metal film surrounded by air, the resonance condition is not well matched to initial plasmonic oscillation mode. Due to this reason, as shown in Fig 3.2.1, the transmission ratio is not high. Fortunately, the refractive index difference between PI and glass is decreased as 0.11 compared with 0.51 between glass and air. Therefore, the deviation of initial plasmonic mode and light re-emission condition are decreased and the transmittance is more enhanced.

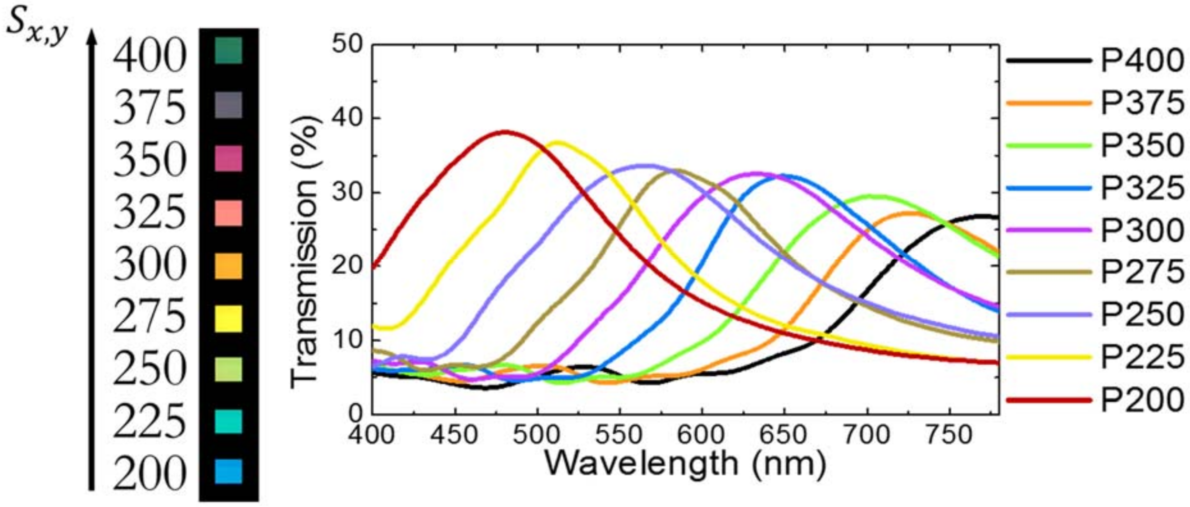


Fig 3.5.3.1 Optical micro-photograph and measured transmission spectra of symmetric design for unpolarized incident light, after coating alignment layer on plasmonic color filter.

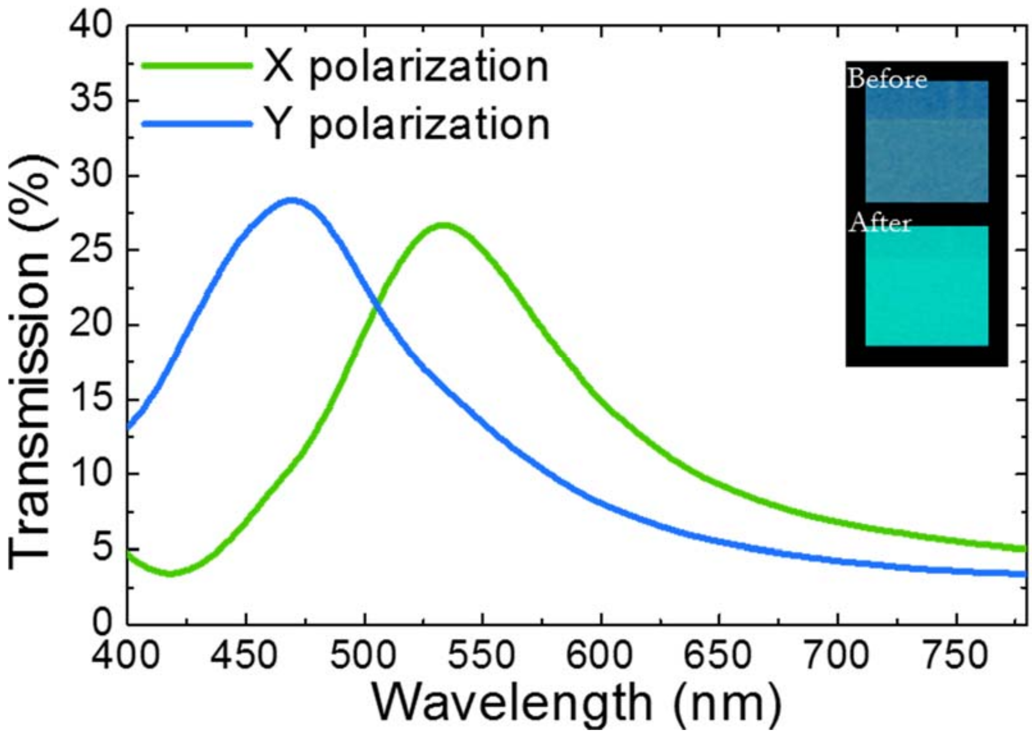


Fig 3.5.3.2 Measured transmission spectra of one specific design(S_x= 225nm, S_y= 225nm) for unpolarized incident light when color filter contact with air and alignment layer. The position of peak is varied from 425 to 512nm

As shown in the Fig 3.5.3.3, various colors such as red, magenta, yellow, orange, green, and blue are presented. However, owing to red shift, pure blue color is disappeared in the 200nm spacing. Therefore, blue resonance peak requires smaller spacing between holes below 200nm. At the device having 400nm spacing, (1,1) peak present dim blue color. This disappears of blue color is not serious problem. Because it can be fixed by lowing spacing factor.

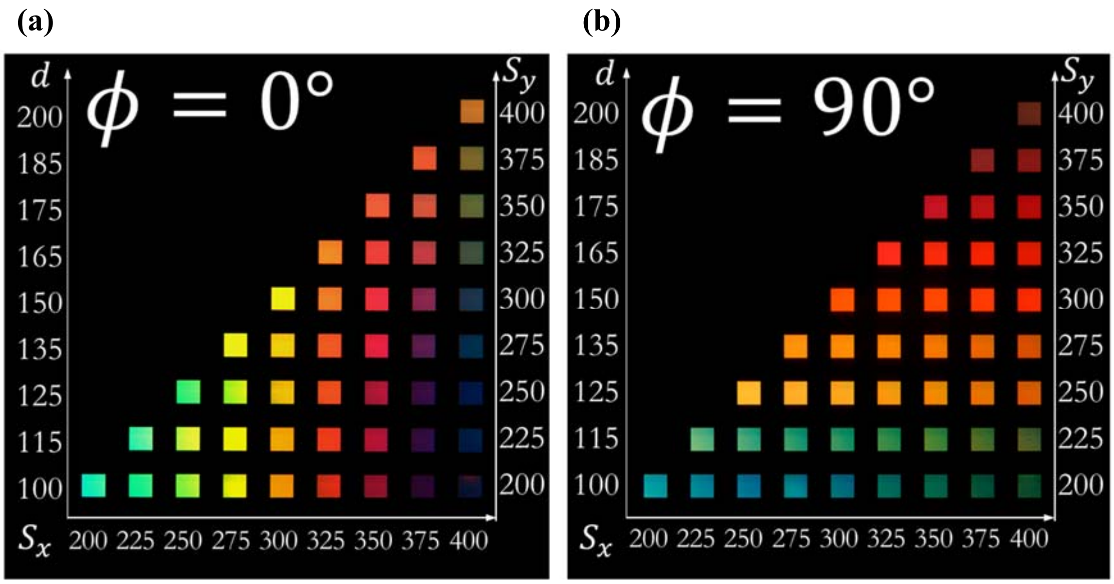
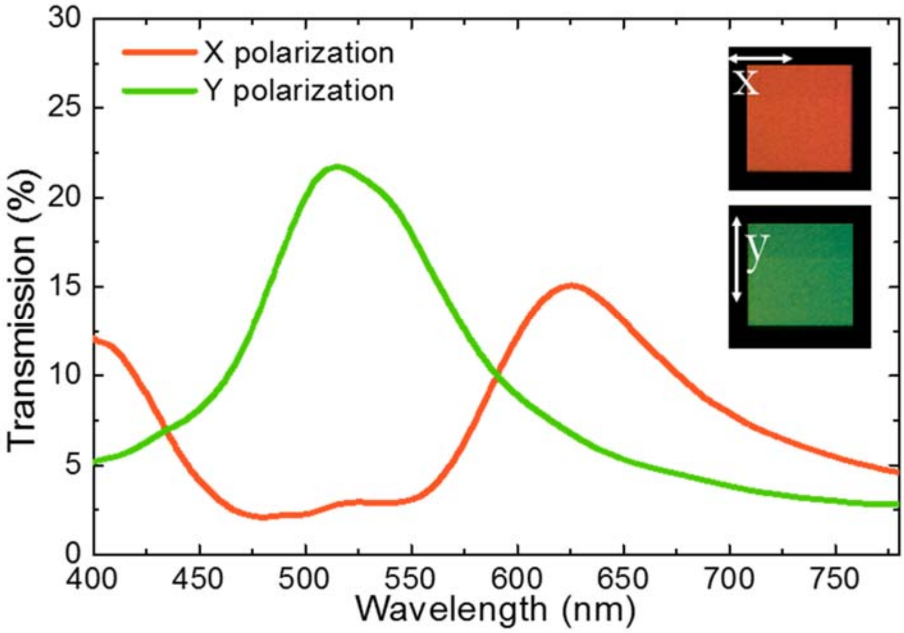


Fig 3.5.3.3 Optical micro-photograph of multi-color filter for 0°(a), and 90°(b) incident polarization, after coating alignment film.

As shown in the Fig 3.5.3.4, asymmetric color filter is presented which have two resonance modes for individual polarization state. Color change is clearly revealed by 0° and 90° polarization state of the incident light. When the x polarized light incidents to nanohole color filter structure, overall, transmission is lower than y polarized case (Fig 3.5.3.4). The reason is that the diameter of hole is set to be optimized more to spacing in y direction. Therefore, if x polarized light incidents to color filter structure, the proportion of hole area is smaller and light is more prevented by aluminum film than y direction case. It is also obvious in the SEM image (Fig 2.2.1.2) It is assumed that ellipse shape hole design can be better for this multi-color filtering structure. Fig 3.5.3.4 shows the optical characteristics of representative filter structures of red-green and green-blue combination. The asymmetrically designed color filter is presented which have two primary resonance modes depending on polarization state.

(a)



(b)

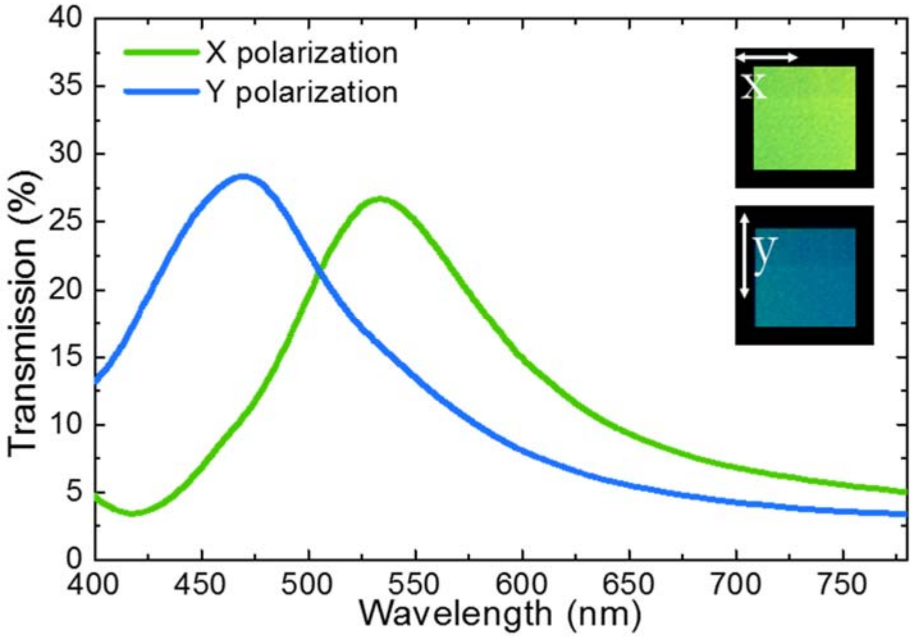


Fig 3.5.3.4 Optical micro-photograph and measured transmission spectra of specific design of (a) $S_x = 325$nm, $S_y = 225$nm and (b) $S_x =250$nm, $S_y = 200$nm.

3.5.4 Characteristics of LC Combined Color Filter

After investigating the effect of alignment layer, the characteristic of active plasmonic color filter is studied. In order to make electrically tunable polarized optical shutter, twisted nematic(TN) mode of LC(E7, Merck) was employed to nanohole array structure. PI solution (SE-5811, Nissan chemical) was spin coated on the nanohole array structure on a glass substrate and the other indium-tin-oxide (ITO) coated glass. One of the most important features is that the nanohole array structure can have a role of electrode together light filtering effect differ from commercial color filter based on color pigments since the base material of nanohole array structure is metal (Al). Therefore, besides inducing two primary color modes, the device structure can be more simplified.

As shown in the Fig 3.5.4.1, the optical microphotograph and spectra are measured and it shows good color distribution in visible wavelength. The maximum transmission of spectra is about 40% and it is enough for color filter. Also, added LC layer makes additional red-shift (Fig 3.5.4.2). At the 275nm spacing of device, yellow color is changed to orange color when LC layer is combined. This red shift is caused by increased refractive index of LC. Although the alignment layer prevents direct contact between LC layer and plasmonic color filter, the resonance property is affected by LC owing to deep penetration depth of surface plasmon wave in dielectric material.

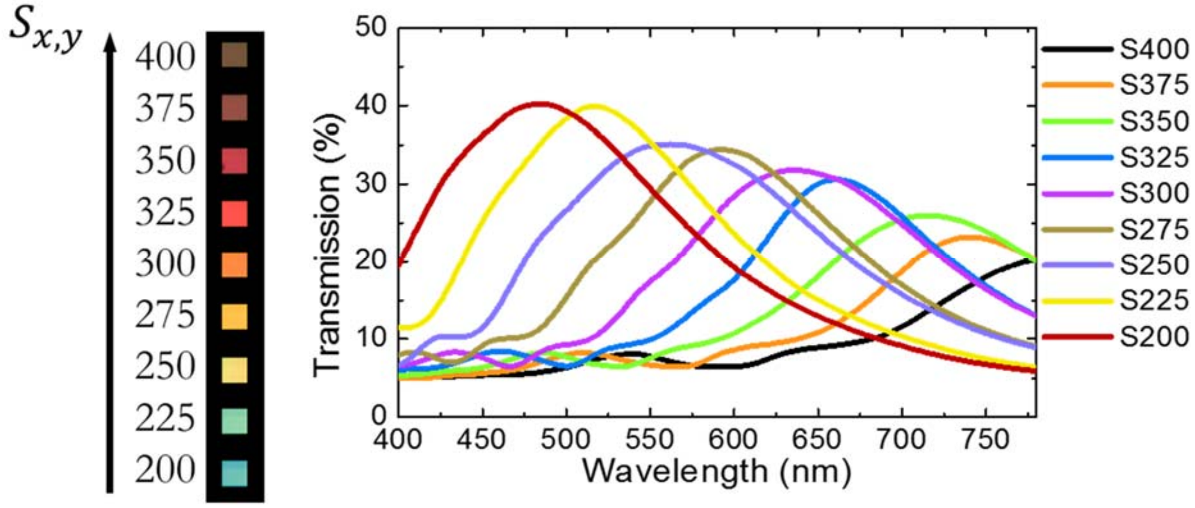


Fig 3.5.4.1 Optical micro-photograph and measured spectra of symmetric design after combing LC

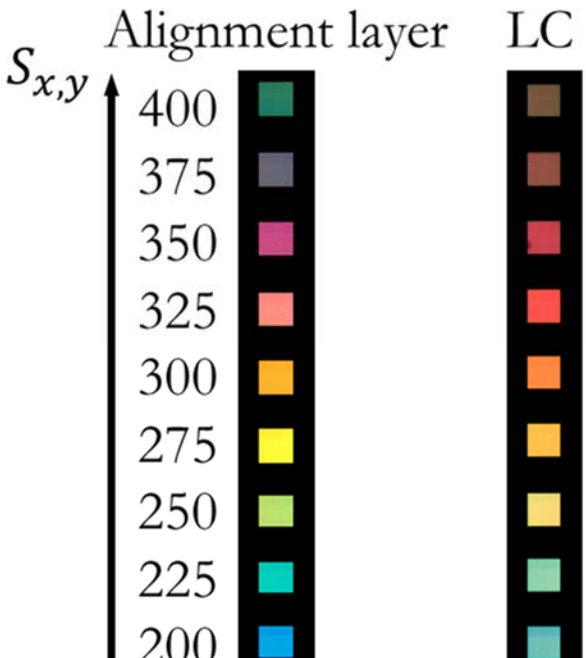


Fig 3.5.4.2 Optical micro-photograph of symmetric design with alignment layer and LC on alignment layer

Fig 3.5.4.3 shows the optical characteristics of combined structure of an asymmetric plasmonic color filter and TN LC cell. Without applied bias (0V), since the top LC alignment is parallel to y-optical axis while the bottom LC directors are rotated 90°, the incoming linearly polarized light, produced by y-direction polarizer follows adiabatically the molecular twist and rotates 90°, i.e., the polarized direction is changed to x-direction. Therefore, the color light is decided by the x-direction geometry of hole array can transmit through the nanohole of plasmonic color filter. In voltage-on state (5V), the LC director is reoriented perpendicular to the substrate, except the boundary layer. In coming polarized light almost keeps its own polarization direction (y-direction), the other primary color light transmits through the structure due to the different spacing between holes in y-direction. The large range of color is obtained varying the spacing factor of nanohole array structure and electrical field (Fig 3.5.4.3).

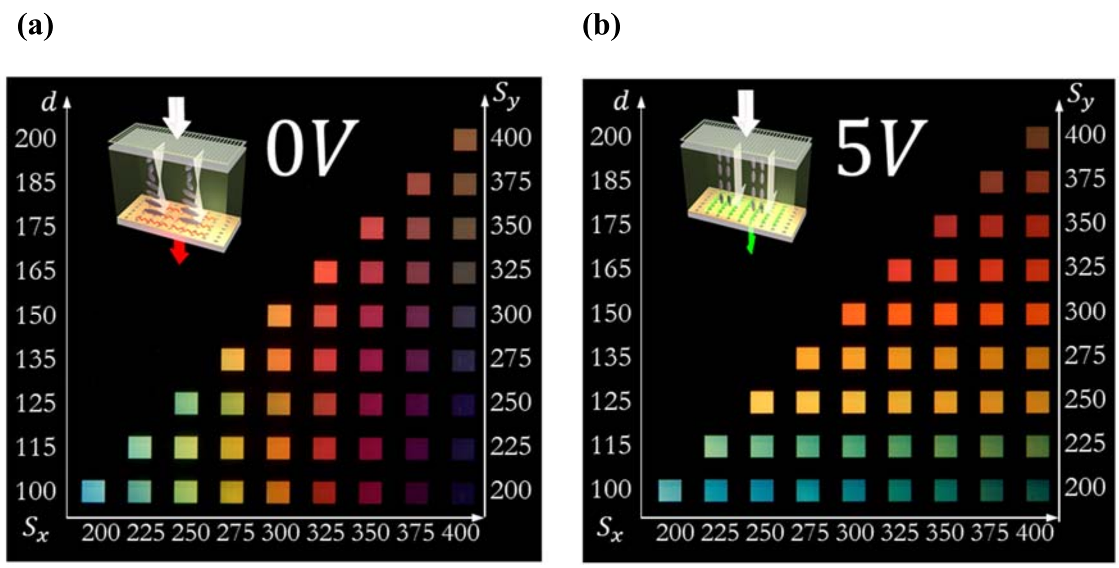


Fig 3.5.4.3 Optical micro-photograph of multi-color filter with y polarization film at 0V (a), and 5V (b), after combining LC layer.

Fabricated color filter can show two primary colors and it has various colors combination between alignment transitions of LC from TN to vertical. The two different color states controlled by electrical field are almost the same as the color states produced by mechanical rotating of polarizer as shown in Fig 3.2.2. By tuning the applied bias, the middle state between two primary colors can easily achieve as like rotating polarizer a little. As shown in Fig 3.5.4.4, any color states in CIE chromaticity diagram between two primary colors can be produced by controlling electrical bias. First design having 200 and 250nm spacing shows color distribution from green to cyan color. And second design having 325 and 200nm spacing, shows color distribution from red to bluish green. Finally, third design having 325 and 225nm spacing, shows color distribution from red to green.

In general display concept, two color dot structures are required to produce similar color results. However, even if the structure is one unit cell structure, it can produce easily multi-color state. Therefore, much higher resolution device can be achieved by employing the device concept. The threshold voltage of this combination cell structure is around 2.5V. It is mainly decided by the opto-electrical characteristics of TN LC cell.

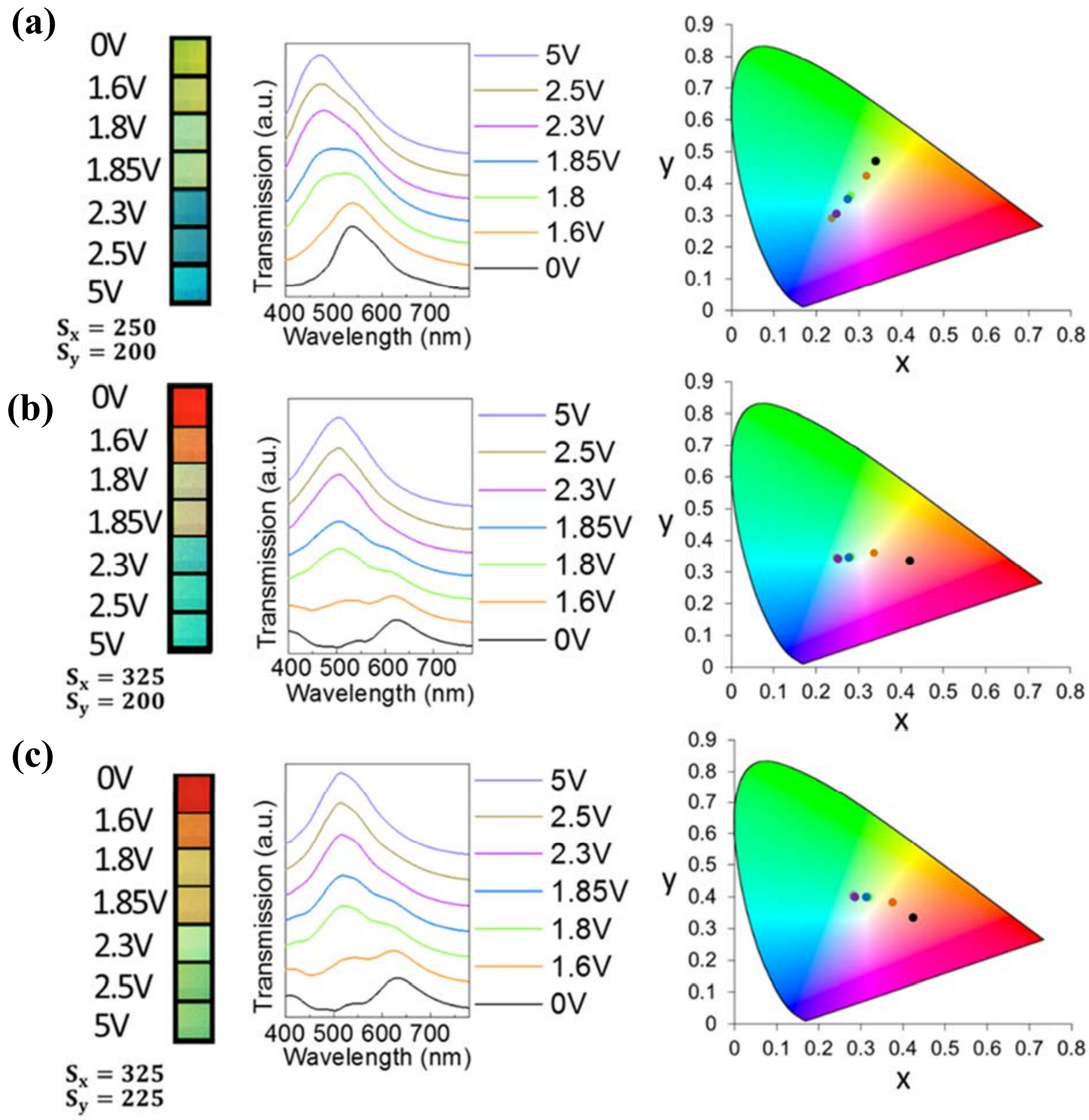


Fig 3.5.4.4 Optical micro-photograph, measured spectra and CIE chromaticity diagram of (a) $S_x = 250$nm, $S_y = 200$ (b) $S_x = 325$nm, $S_y = 200$ and (c) $S_x = 325$nm, $S_y = 225$nm.

LC layer induced a slight change of primary color states. Although the alignment layer prevents direct contact between LC layer and plasmonic color filter, the resonance property is affected a little by LC owing to deep penetration depth of surface plasmon wave in dielectric material. Therefore, if the alignment direction of LC is changed, the resonance condition of nanohole arrays will be also affected. In order to figure out these phenomena, the effect of liquid crystal at the symmetric design are tested (Fig 3.5.4.5). Although there are no polarization effect, some red shift appears with electric field. This effect is mainly due to basic plasmonic principle. Surface plasmon wave has both lateral and vertical electronic wave. In the dielectric layer, the effect of vertical direction of electronic wave is larger than lateral direction of electronic wave. Therefore, in contrast with random oriented LC state, vertical alignment of LC director has higher refractive index and lateral alignment of LC director has lower refractive index. When electrical bias is applied to LC, LC has a higher refractive index due to vertically aligned state and final color shifts to longer wavelength than designed value. Therefore, if electrical on state matches to long axis direction of asymmetric hole array design, more various color states can be expected from one unit cell structure.

If we use this additional effect, we can make more tunable color filter. If we select LC having large birefringence, the amount of shift is widely extended. Also, if there are multi-mode controls of liquid crystal using both polarization and dielectric constant effect, we can get more useful color filter to emit various colors.

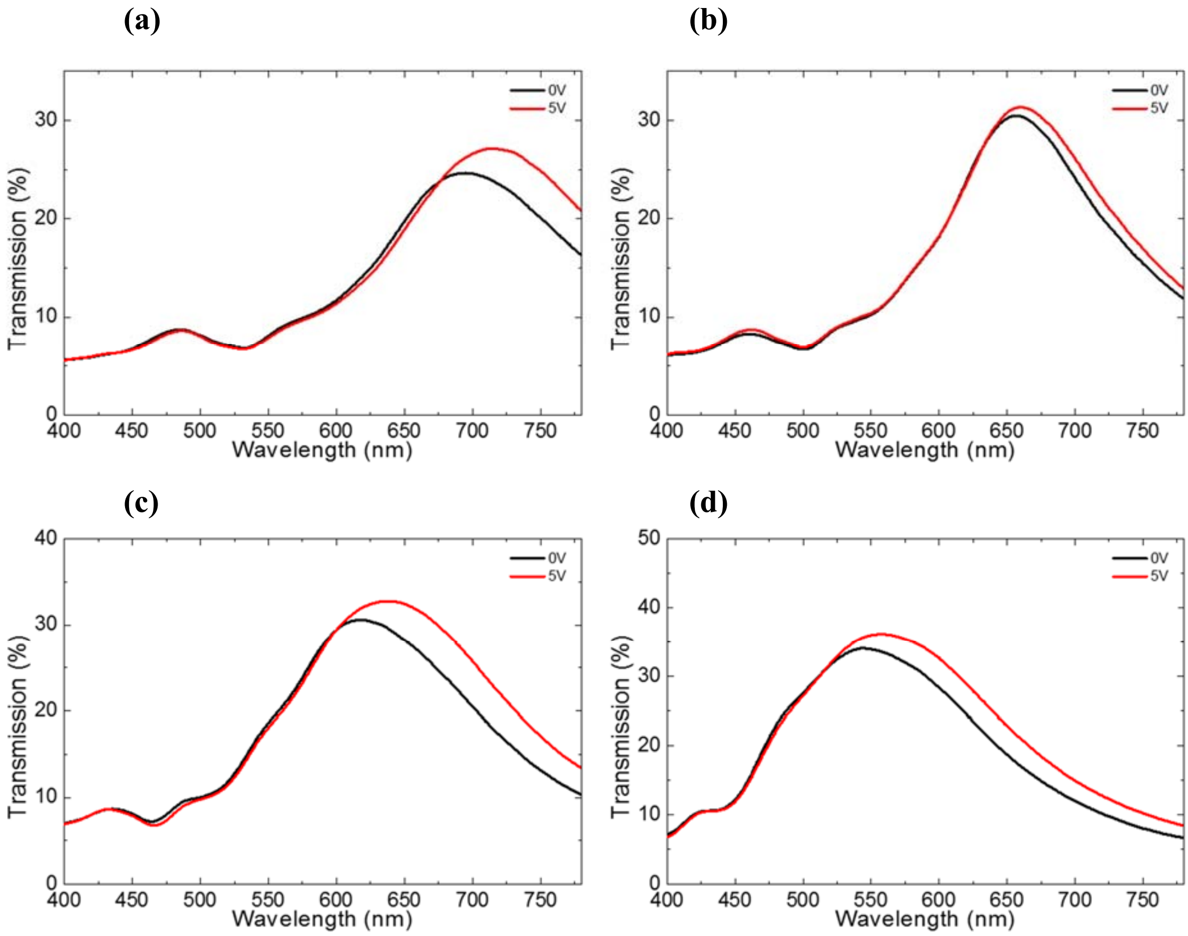


Fig 3.5.4.5 Measured Spectra of symmetric design considering shift by only change of refractive index. $(a) S = 350nm, (b) S = 325nm, (c) S = 300nm, (d)\ S = 275nm$

IV. CONCLUSION

We designed and fabricated liquid crystal based active tunable color filter that has polarization rotator on plasmonic color filter. To give activity to the plasmonic color filter, asymmetric design is selected and this color filter can show different colors with the variable polarization state of incident light. However, this type of color filter need additional polarization variable system. In order to give more activity to plasmonic color filter, we studied the sensitivity of dielectric constant based method and additional polarization rotator system. The former case was studied using symmetric nanohole arrays and liquid crystal. We fabricated symmetric design of nanohole arrays to study only the effect of dielectric constant. After combining liquid crystal to plasmonic color fitler, the variable range of shift of wavelength peak are around 13nm and it was small owing to its small birefringence. However, if other liquid crystal having high birefringence is used, the range of wavelength shift will be extended.

In the latter case, the polarization rotator method, twisted nematic(TN) mode cell was assembled on nanostructure. The LC combined plasmonic color filter was able to change its color as modulating the amount of transmission of two fixed wavelength peaks, so that the various colors were obtained. We can easily modulate the color of device by only variable electric field. The effect of alignment layer and liquid crystal to the wavelength shift were also considered for designing more exact color filter system.

This type of color filter can realize high resolution color filter because the sub pixels were not necessary to make combination of three colors such as red, green, and blue. In our research, we made tunable color filter having two main peaks such as green, and red. If additional driving modes are combined to make multi-function color filter with high birefringence liquid crystal, we can get three principle colors at one device. Then, we don't need sub pixel to present desire color.

The results demonstrate that our active plasmonic color filter could be useful to the color system to realize more high resolution and further meaningful application.

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요 약 문

전기적으로 색을 조절 가능한 금속 나노구조체 기반의 광학 셔터

본 연구는 기존의 컬러필터의 수동적인 한계점을 극복하기 위해 능동적인 컬러필터를 개발하는 것에 초점을 두고 있다. 플라즈모닉스가 등장한 이래 빛의 성질을 변화시키는 그 특성을 이용하여, 컬러필터, 바이오센서, 이미지 레코딩 등 수많은 관련 연구들이 진행되고 있다. 특히 현재 주로 사용되는 형광 컬러필터를 대체할 수 있는 금속 박막의 컬러필터가 주목 받고 있다. 기존에 사용하던 형광물질을 이용한 컬러필터는 광 효율이 낮고, 복잡한 공정을 요구하며, 자외선에 의해 쉽게 손상되는 등 많은 한계점을 지니고 있다. 플라즈모닉 컬러필터를 사용하여 간단한 공정으로 고효율의 컬러필터를 실현할 수 있다. 그러나 이러한 컬러필터 또한 한번 제작되면 그 특성을 변화시킬 수 없다는 한계점을 지니기 때문에 원하는 색을 표현하는데 3 개의 서브픽셀이 필요하여 고 해상도 디스플레이에 불리하다. 이러한 문제점을 해결하여 한가지 컬러필터에서 여러 가지 색을 나타내어 기존과 다른 컬러 시스템을 구현하는 것이 도전과제이다.

본 논문에서는 플라즈모닉 구조체에서 발생하는 편광 선택적인 특성을 이용하여 전기적으로 색을 변화시킬 수 있는 능동적인 컬러필터가 연구되었다. 나노미터 크기의 구멍들이 알루미늄 박막에 나열된 구조체를 제작하여 특정 파장대의 입사광만 투과 시키는 컬러필터를 제작하였다. 또한, 나노 구조체들을 특수한 구조로 배열하여 배열의 방향마다 다른 증폭 특성을 보이도록 제작했다. 이러한 비대칭적인 컬러필터는 입사하는 빛의 편광에 따라서 다양한 색을 나타내는 성질을 지니고 있기 때문에, 투과 특성이 한가지 색으로 고정되지 않는다. 더욱 유용하게 색을 조절하기 위해서 액정을 이용한 편광셔터를 추가로 결합했다. 액정을 이용한 편광셔터는 전기적인 신호를 이용하여 자유자재로 색을 변환시킬 수 있는 장점을 지닌다. 또한, 한가지 픽셀에서 수많은 색을 나타낼 수 있으므로 고해상도의 디스플레이를 구현할 수 있다. 이러한 점에서 본 능동적인 컬러필터는 기존과 다른 컬러 구현 방식을 가지고, 고해상도의 디스플레이에서 활용될 수 있다는 점에서 의의를 가진다.

핵심어: 능동적인 컬러필터, 플라즈모닉 구조체, 편광셔터

Acknowledgements

This thesis would not have been possible to write this master's thesis without the help and support of the kind people around me, to only some of whom it is possible to give particular mention here.

Above all, I would like to express my deepest gratitude to my supervisor, Prof. Jae Eun Jang, for his unwavering support and guidance throughout this thesis. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my master study.

Besides my advisor, I wish to thank the members of my dissertation committee: Prof. Chang-Hee Cho and Prof. Jae Youn Hwang; They guided me to widen my research from various perspectives.

I would like to thank member of KNU: Jun-Chan Choi, Min-Kyu Park and Prof. Hak-Rin Kim; Much of my experimental work would have not have been completed without assistance of them.

And, I also would like to thank member of Advanced Electronic Devices Research Group: Jeong Hee Shin, Gwang Jun Lee, Seunguk Kim, Jaehoon Yang, Minkyung Sim, Byoung Ok Jun, Kwonsik Shin, Jonghyeun Kim, Seungchul Lee, Hyunchul Park, and Sujin Heo; They have usually given me a help and advice for research during the process in doing this dissertation.

Lastly, I wish to express my sincere gratitude to my family for their encouragement and moral support.