

An optical system adopting liquid crystals with electrical tunability of wavelength and energy density for low level light therapy

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ABSTRACT

We have developed a bistable negative lens by integrating a polarization switch of ferroelectric liquid crystals (FLCs) with a passively anisotropic focusing element. The proposed lens not only exhibits electrically tunable bistability but also fast response time of sub-milliseconds, which leads to good candidate of optical component in optical system for medical applications. In this paper, we demonstrate an optical system consisting of two FLC phase retarders and one LC lenses that exhibits both of electrically tunable wavelength and size of exposure area. The operating principles and the experimental results are discussed. The tunable spectrum, exposure area size and tunable irradiance are illustrated. Compared to conventional lenses with mechanical movements in the medical light therapy system, our electrically switchable optical system is more practical in the portable applications of light therapy (LLLT).

Keywords: Liquid crystal lens; Low level light therapy; Ferroelectric liquid crystals; Lyot-Ohman filter

1. INTRODUCTION

In dermatology and dentistry, the interaction between light and human body has been applied to several kinds of therapies such as ablation, photothermolysis¹⁻² and low level light therapy (LLLT)³⁻⁶. The mechanism of LLLT is that the photons of the light source are absorbed by molecular photoacceptor and then trigger natural intracellular photobiochemical reactions, which is also called biostimulation. The biological effects of the reaction depend on the parameters of the irradiation such as wavelength, energy intensity and treatment time. The power of light source for LLLT is lower than 100mW and the wavelength ranges from 300nm to 1100nm. In addition, wavelength of 630nm to 850nm is proved to be effective on wound healing, inflammation diminishing and photorejuvenation by means of stimulating the cells to produce adenosine triphosphate⁷⁻⁸. Wavelength of 415nm is irradiated to cure propionibacterium acnes by killing the bacteria⁹. Green light with wavelength of 550nm is claimed to deal with hyperpigmentation.¹⁰

A biphasic response described by Arndt-Schulz Law states a proper energy density for all treatments¹¹. Energy density in a unit of J/cm² of LLLT is:

$$\text{energy density}(J / \text{cm}^2) \equiv \text{power}(W) \times \text{time}(\text{sec}) / \text{area}(\text{cm}^2) = \text{irradiance}(W / \text{cm}^2) \times \text{time}(\text{sec}). \quad (1)$$

This indicates we can control the energy density by adjusting the three parameters: power(W), time(s) and irradiation area(cm^2). Usually the energy density used in LLLT is in the range of 1~4 J/cm^2 . Moreover, LLLT is required both of tunability in wavelength and energy density. Conventionally, multiple light sources are used in LLLT portable devices and the energy density in the treatment area is controlled by mechanical movement of several solid lenses which leads to bulky systems. A Liquid crystal lenses shows tunable lensing effect after we apply an inhomogeneous electric field to induce inhomogeneous refractive index. Recently, we developed a bistable liquid crystal lens based on integrating a polarization switch of ferroelectric liquid crystals (FLC) and a passive polymeric lens¹². The function of FLC is a phase retarder; however, the dispersion of FLC results in color breakup which means different lens power at different wavelengths. In this paper, we proposed a portable LLLT devices based on three polarizers, three LC cells as phase retarders and one LC lens with a continuously tunable lens power. The dispersion of LC cells can help to select three wavelengths of light and the beam size can also be adjusted by the LC lens. The operating principle and experiments are introduced and demonstrated.

2. OPERATING MECHANISM AND EXPERIMENTAL SET UP

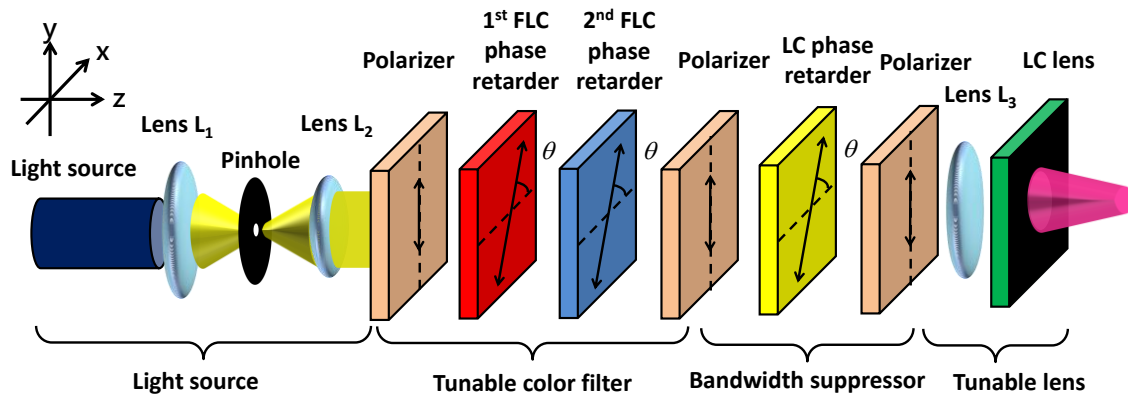


Fig. 1 The structure of the proposed optical system for portable LLLT.

The structure of the proposed optical system for LLLT is depicted in Fig. 1. The optical system consists of four parts: a white light source, a tunable color filter, a bandwidth suppressor and a tunable lens. The white light source is a LED device (TouchBrigh TB-X3-RCPI). Two lenses (L_1 and L_2) and a pinhole are used to collimate the light. The lens power of the solid lens (L_1) and solid lens (L_2) are 20 diopter and 50 diopter, respectively. In the part of tunable color filter, it consists of two polarizers and two tunable FLC retarders. The transmissive axes of two polarizers are parallel to y direction and the alignment direction of the FLC retarders is 45 degrees with respect to x-axis. The transmittance of light after light propagates through two polarizers and two FLC phase retarders is :

$$\frac{I_{out}}{I_{in}} = \frac{1}{2} \left| \sin^2 \theta + \cos^2 \theta (e^{i\Gamma}) \right|^2, \quad (2)$$

where Γ is the retardation of the retarder, θ is the angle between the fast axis of the FLC phase retarder and the

transmissive axis of the polarizer¹³. When θ is 45 degree, Γ satisfies Eq.(3) for maximum transmittance of light ($I_{out}/I_{in}=0.5$):

$$\Gamma = \frac{2\pi \times \Delta n \times d}{\lambda} = 2N\pi, \quad (3)$$

where λ is wavelength, d is thickness or cell gap, Δn is birefringence ($=0.17$ for FLC) and N is integer. To design three center wavelengths: 450nm, 550nm and 650nm, the cell gaps (d_{450} , d_{550} , d_{650}) are $2.65 N_1$, $3.23 N_2$, $3.82 N_3$, respectively. N_1 , N_2 , N_3 are three integers. The effective fast axis of a FLC cell can be switched along $\theta=45^\circ$ at +10 V or $\theta=0^\circ$ at -10 V. After we set the proper cell gaps in tunable color filter part in Fig. 1, the white light passes through tunable color filter part as $\theta=0^\circ$ of two FLC cells which leads to no wavelength selection (defined as off-state) because the y-linearly polarized white light does not change the polarization state. On the contrary, light of a certain wavelength passes through tunable color filter part as $\theta=45^\circ$ of two FLC cells (defined as on-state) because the y-linearly polarized white light experiences phase retardation to reach maximum transmittance at certain wavelength. We could also design different cell gaps in two FLC phase retarders for different wavelengths. For example, $d=2.65\mu\text{m}$ for 450nm for the 1st FLC phase retarder and $d=3.82\mu\text{m}$ for 650nm for the 2nd FLC phase retarder. When the 1st FLC phase retarder is at on-state and the other one is at off-state, the optical path difference of two cells is $0.45 \mu\text{m}$ and the light passes through the polarizer is blue because the blue light has maximum transmittance. The optical system is operated in blue mode. When the 1st FLC phase retarder is at off-state and the other one is at on-state, the optical path difference of two cells is $0.65 \mu\text{m}$ and the light passes through the polarizer is red because the red light has maximum transmittance. The optical system is operated in red mode. When both of the FLC phase retarders are at on-state, the optical path difference of two cells is $1.01 \mu\text{m}$ and the light propagates after the polarizer is green because the green light has maximum transmittance. The optical system is then operated in green mode.

Fig. 2(a) is simulation results of the light intensity as a function of wavelength for the tunable color filter part only. The blue triangles, red squares and green dots stand for blue mode, red mode and green mode, respectively. As once can see in Fig. 2(a), the center wavelengths in three modes are 450 nm, 550 nm, and 650 nm. The full width at half maximum (FWHM) in wavelength is 239.4nm for blue mode, 245.4nm for red mode, and 131.9nm for green mode. The FWHM are still too broad. In order to narrow the bandwidth, we extra design a Lyot-Ohman filter¹⁴ in the optical system as a bandwidth suppressor in Fig.1. We put an addition LC phase retarder behind the second polarizer and followed by a polarizer with its transmissive axis along y-axis. (Fig.1) The fast axis of the LC phase retarder is 45 degrees with respect to the y-axis. The optical path difference is designed around $3.23 \mu\text{m}$. Fig. 2(b) shows the simulation results of the spectrum of the bandwidth suppressor consisting of two polarizers and one LC phase retarder. When we combine tunable color filter with the bandwidth suppressor, this means Fig. 2(a) times Fig. 2(b) and the results show in Figs. 2(c), 2(d), and 2(e). In Figs. 2(c), 2(d), and 2(e), the effective FWHM at center wavelength of 450nm is 32.4 nm, 42.6 nm at 550nm, 63.6 nm at 650 nm. FWHMs of three modes are less than 100nm under an assistance of the bandwidth suppressor.

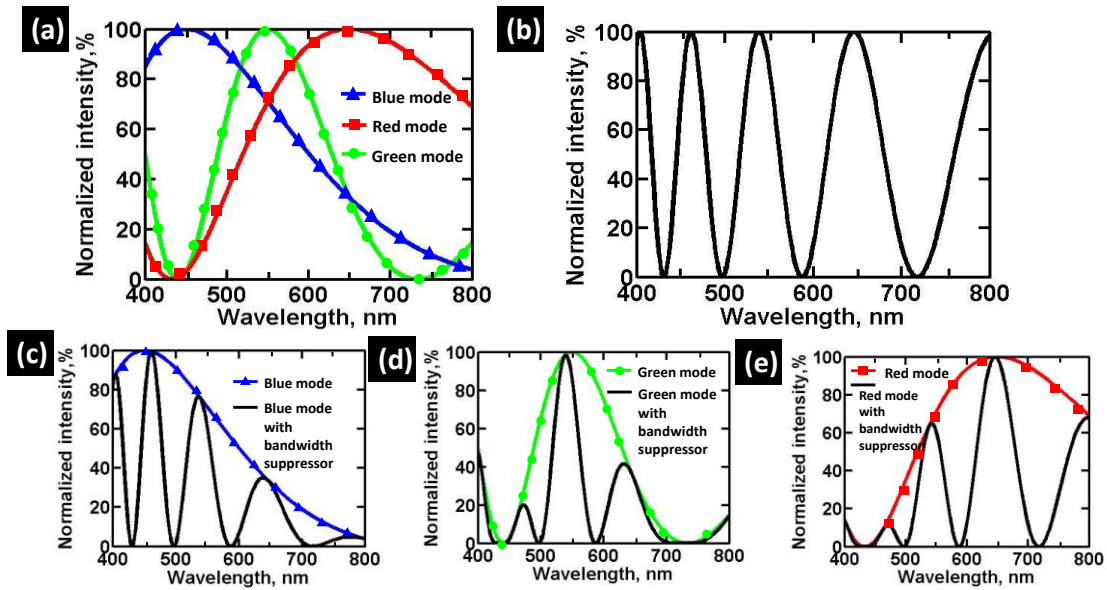


Fig 2. Simulation of transmission spectrum of the tunable optical system (a) without bandwidth suppressor, (b) transmission spectrum of the bandwidth suppressor (c), (d), and (e) stand for transmission spectra of blue mode, green mode and red mode with the bandwidth suppressor, respectively.

To further manipulate the energy density, the irradiation area should be controllable. We add a solid lens (lens power: 12 Diopter) and a LC lens to assemble “the tunable LC lens part” in Fig. 1. The lens power of the LC lens can be switched continuously from negative one to positive one by applied voltage. When the LC lens is a positive lens, the beam is focused into smaller area and produce higher irradiance. On the other hand, when the LC lens is a negative lens, the beam is dispersed into larger area and produce lower irradiance. Thus, we are able to realize the optical system with both tunable wavelengths and optical density for LLLT applications by constructing the structure in Fig. 1.

In sample preparation, two FLC cells are that FLC materials (Felix-017/000) are sandwiched between two ITO glass substrates coated with mechanically rubbed polyimide layers (Mesostate LCD industries) in anti-parallel directions. The cell gaps of two FLC cells were $2.65\mu\text{m}$ and $3.82\mu\text{m}$. The LC cell for the bandwidth suppressor is that nematic LC (E7) is sandwiched between two ITO glass substrates coated with mechanically rubbed polyimide layers (Mesostate LCD industries) in anti-parallel directions. In order to meet the optical path difference we design ($3.23\mu\text{m}$), the LC cell for the bandwidth suppressor was applied voltage of $1.75\text{ V}_{\text{rms}}$ ($f=1\text{kHz}$). As to LC lens, we adopted the LC lens with double-layered structure with a hole-patterned electrode and a flat electrode.¹⁵ However, two LC layers are aligned parallel, not orthogonal. The electric fields distributed to LC layers are controlled by a hole-patterned electrode and a flat electrode. While the applied voltage of the hole-patterned electrode is higher than the flat one, the LC lens is a positive lens. The LC lens is a negative lens in the opposite way of electrode controls. The measured lens power of the LC lens ranges from -1.7 to $+2.0$ diopter.

3. RESULTS AND DISCUSSION

3.1 Transmission spectra of the retarders

After we fabricated two FLC phase retarder cells: the 1st FLC phase retarder with cell gap of 2.6 μm and the 2nd one with a cell gap of 3.8 μm , we measured transmissive spectra of the tunable color filter part. The LED light (TouchBright TB-X3-RCPI) was used as a white light source. Two solid lenses and a pinhole were used to collimate light. In order to construct the part of the tunable color filter (Fig. 1), two FLC sample was placed between two polarizers whose transmissive axes are parallel to each other (y-axis in Fig.1). A spectrometer (USB-2000, Ocean Optics) was used to measure the spectra. The measured spectra of tunable color filter without bandwidth suppressor are shown in Fig 3(a). The lines with blue triangle, red squares, green dots represent blue mode (i.e. 1st FLC is on, 2nd FLC is off), red mode (i.e. 1st FLC is off, 2nd FLC is on), and green mode (i.e. both of FLC cells are on), respectively. The detail operation of three modes is introduced in the previous session. In Fig. 3(a), the center wavelengths of three modes are located in 450nm (blue mode), 550nm (green mode), and 650 nm (red mode). The FWHM values are 171.3 nm at center wavelength of 450 nm, 92.3 nm at center wavelength of 550 nm, and 213.1 nm at center wavelength of 650 nm. In Fig. 3(b) shows the spectra after the bandwidth suppressor. As one can see the FWHM near the center wavelengths are suppressed. After the bandwidth suppressor, the FWHM values are 28.3 nm at center wavelength of 450nm, 44.6 nm at center wavelength of 550 nm, and 84.9 nm at center wavelength of 650 nm. However, the transmittance decreases in Fig. 3(b) because of the polarizer and multiple reflections of the interfaces. In addition, the side lobes appear outside the center wavelengths which could be reduce by enlarging the optical path differences of the phase retarders while even narrower the values of FWHM.

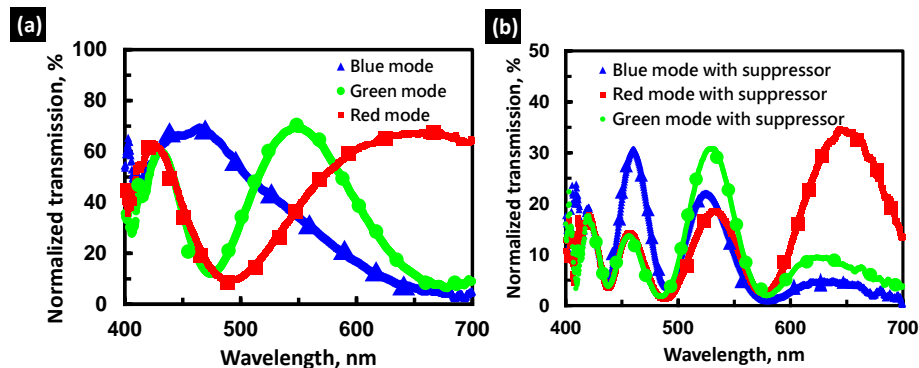


Fig 3. Transmission spectra (a) without bandwidth suppression, (b) with bandwidth suppression.

3.2 Tunable irradiance by a liquid crystal lens

To further demonstrate the tunable irradiance, we added a solid lens and a LC lens to the three phase retarders (Fig. 1). The function of the solid lens is to adjust the beam size $\sim 10\text{mm}$ in diameter which is incident to the liquid crystal lens. The lens power of the liquid crystal lens is electrically tunable from +2 Diopter to -1.7 Diopter. By means of tunable lens power to change the beams size at the exposure area, the irradiance or energy density could be

adjustable. To measure the area change of the exposure area, we placed a diffusor 7cm away from the LC lens and took images at different lens power of the LC lens and at different modes of three LC phase retarders by a camera (sony RX100-m3). The recorded images are shown in Fig. 4(a). The three images of the first row in Fig. 4(a) show the difference beam size at different lens power of the LC lens at the red mode. The second and the third rows are for the green mode and blue mode. The beam spots are slightly enlarged (0.7mm to 0.9mm in diameter) when the lens power changes from +2 Diopter to -1.7 Diopter. We also plotted irradiance as a function of beam size in Fig 4(b). The tunable range of the irradiance for all three wavelengths is around 0.6 to 1 mW/cm². The irradiance decreases with the beam size which results from the lens power of the LC lens. As a result, the optical system we proposed in Fig. 1 not only has capability of a selection of three wavelengths, but also switchable irradiance of the light at certain wavelength. By multiplying irradiance by time, this also means energy density is tunable. For the practical application, the energy density (or fluence) in our system can reach 2.16~3.6 J/cm² with treatment time of 60 min. The treatment time is still too long for a portable light therapy device. This problem can be solved by decreasing the power loss of the optical system in terms of removal of multiple reflections. The treatment time can be around 15 minutes when the irradiance of the output light is in the range of 1~4.5mW/cm².

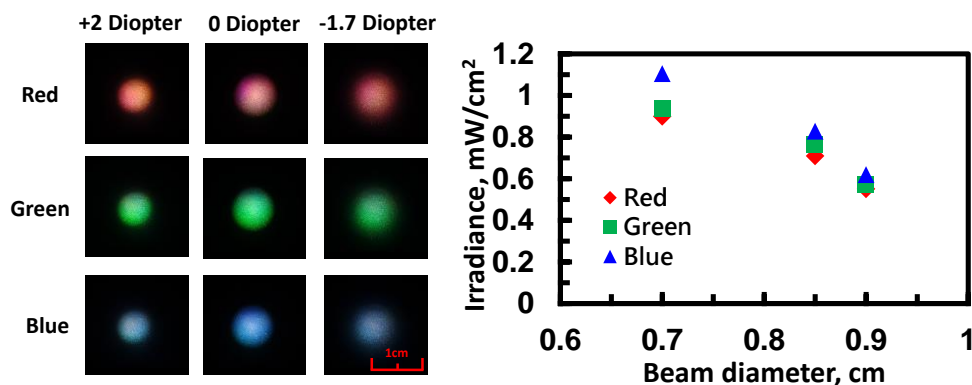


Fig 4. (a) Irradiation area profile and (b) irradiance with different color and lens power.

4. CONCLUSION

We demonstrate a low level light therapy optical system with electrically tunable wavelength and energy density. The system includes a LED light source, two FLC phase retarder as a tunable color filter, a LC phase retarder as a bandwidth suppressor and a tunable liquid crystal lens. We can electrically control the output wavelength by tuning the retardation of the FLC cell in three modes: blue mode with central wavelength of 450nm, green mode with central wavelength of 550nm and red mode with central wavelength of 650nm. The bandwidth of the peak wavelength is suppressed by adding Lyot-Ohman filter to less than 100 nm. The energy density is manipulated from 0.6 to 1 mW/cm² by tuning the exposure area size with a liquid crystal lens. The optical device can be applied to portable LLLT devices with tunable wavelength and dose function.

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