Concentrating Photovoltaic System Using a Liquid Crystal Lens

Yu-Shih Tsou, Yi-Hsin Lin, and An-Chi Wei

***Abstract*— A concentrating photovoltaic (CPV) system with a steady electric output adopting an electrically tunable concentration ratio of the liquid crystals (LC) lens is demonstrated. The distribution of the LC directors of the LC lens can be controlled by an applied voltage in order to adjust the number of incident photons in an area. As a result, the CPV system adopting an LC lens can be operated with a static and maximum output power density under different ambient illuminations because the LC lens with an electrically tunable concentration ratio helps to increase the photocurrent at a low illumination and prevent the effect of the series resistance at a high illumination. The detailed operating principles are discussed, and the experimental results are performed. We believe this letter can help enhance the output power density of CPV systems by using active optical elements whose concentration ratio is tunable.**

***Index Terms*— Concentrating photovoltaic, liquid crystal (LC), liquid crystal lens.**

I. INTRODUCTION

A SOLAR cell is a device that converts the energy of sunlight directly into electricity [1]. A concentrating photovoltaic (CPV) system, collecting light over a large area and then focusing the light into a small area of solar cell, is one of the main methods to enhance the efficiency of the solar cell (i.e. the ratio of output electric power to input power of light) [2]. In the CPV system, Fresnel lenses have been utilized as focusing elements to increase the number of photons entering the solar cell as well as enlarge the photocurrent density of the solar cell. When the photocurrent density is low which also causes low output current of the solar cell, we can ignore the power consumption induced by the series resistance which arises from the contact resistance, base bulk resistance, sheet resistance of the emitter, metallic resistance of the emitter and metallic resistance of the electrode [3]. However, the power consumption induced by the series resistance cannot be ignored at a high photocurrent density. As a result, the output power of the solar cell drops dramatically and then the efficiency of the solar cell is reduced. Such an effect of series resistance is especially sensitive to the variations of the ambient sunlight or weather conditions [4], [5]. Owing to fixed focusing properties of the Fresnel lens in a CPV system, the Fresnel lens only provides a constant concentration ratio which is defined as the ratio of the area (or the aperture) of a Fresnel lens to the area of the solar cell. As a result, the CPV system adopting the Fresnel lens is less efficient under the various illumination conditions or the ambient sunlight. Therefore, it is important to improve output power density of CPV systems. Liquid crystals (LCs) are excellent electro-optical materials which can improve the solar cell. The anisotropic and ordering properties of LCs have been used to improve efficiency in a dye-sensitized solar cell [6], and the thermal properties of cholesteric LCs have been used to determine local shunts [7]. Actually, the LC is also good at modulation of an incident light, such as amplitude and phase modulation [8]. On the basis of the phase modulation, LC lenses with electrically tunable focusing properties have been developed for years [8]–[11]. The main mechanism of LC lenses is based on the changes of the distribution of refractive indices of an LC layer resulted from the electrically switchable orientations of LC directors, and then the phase of incident light is modulated. Thus, the concentration ratio of LC lenses is electrically switchable, unlike conventional Fresnel lenses. LC lenses have great potential to overcome the problem of the variable output power density of the CPV system due to the variation of power consumption induced by the effect of series resistance. In this letter, we demonstrate a CPV system with a the highest and a steady electrical output by adopting an electrically tunable concentration ratio of the LC lens because the LC lens helps to increase the photocurrent at a low illumination and prevent the effect of the series resistance at a high illumination. We believe this letter opens a window to enhance the output power density of CPV systems by using active optical elements.

II. OPERATING PRINCIPLES

The operating principles of the proposed CPV system adopting an LC lens are illustrated in Fig. 1(a) and (b). The system consists of an LC lens, a multi-junction solar cell, and a DC-AC inverter. When the sunlight passes through an LC lens, the LC lens modulates the number of photons per area (or photon-flux density). Two layers of LC are used in order to remove the polarization dependency. The photons are incident into solar cell and then are absorbed in the depletion region. The electron-hole pairs are excited in the depletion region when the energy of photons is larger than the diode band gap. The electrons are then excited from the valence band to the conduction band and then generate the free

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Y.-S. Tsou and Y.-H. Lin are with the Department of Photonics, National Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: yilin@mail.nctu.edu.tw; jameslin@faculty.nsysu.edu.tw).

A.-C. Wei is with Foxsemicon Integrated Technology Inc., Miaoli 350-53, Taiwan (e-mail: an-chi.wei@plenstek.com).

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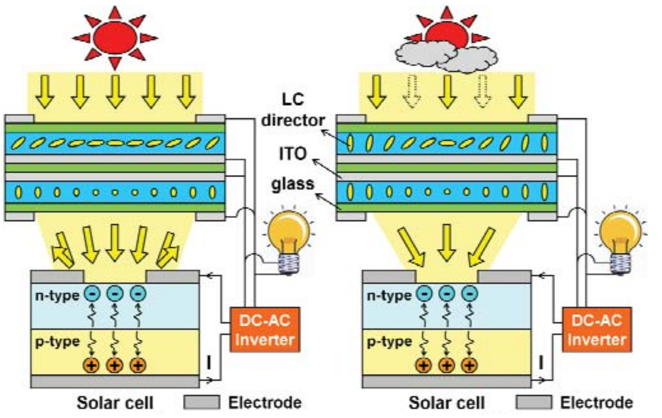

(a) (b)

Fig. 1. Operating principles of CPV system adopting an LC lens under (a) strong illumination and (b) weak illumination.

electrons and holes. The free electrons and the holes move to form a photocurrent. The electric current (I) or directing current (DC) resulting from the drifting electrons and holes can be converted into an alternating current (AC) by a DC-AC inverter. Such an AC can provide electricity to the bulb and the LC lens. The LC lens is a device that the focusing properties change with the applied voltage due to the orientation of LC directors. Under a strong illumination in Fig. 1(a), the low photon-flux density which is modulated by the LC lens enters the solar cell to reduce the effect of the series resistance. Under a weak illumination in Fig. 1(b), the LC orientations of LC lens are adjusted to increase more photon-flux density entering the solar cell in order to enhance the output current. Assume that the mean photon-flux density of sunlight is ϕ_{onesun} and S is a sunlight factor which indicates the variation of sunlight depending on weather conditions. The photon-flux density of the incident light is $S \times \varphi_{\text{onesun}}$. The relation between the photon-flux density from the sunlight and illumination accepted by the solar cell (ϕ_{input}) can be expressed as:

$$\varphi_{\text{input}} = X(V_{\text{LC}}) \times S \times \varphi_{\text{onesun}} \tag{1}$$

where X is the concentration ratio depending on the driving voltage of the LC lens (V_{LC}). Define a parameter $X_S(V_{\text{LC}})$ which is equal to $S \times X(V_{\text{LC}})$ indicates the total concentration ratio or the ratio of ϕ_{input} to ϕ_{onesun}. The illuminated solar cell is a current source with output electrical power density (P_{out}). According to the photogeneration effect of the p-n junction, P_{out} can be expressed as [12]:

$$P_{\text{out}} = J_{\text{SC}} \times V_{\text{OC}} \times FF \tag{2}$$

where J_{SC} is the short circuit current density or the photocurrent density, V_{OC} is the open circuit voltage, and FF is the fill factor which is defined as the ratio of the actual output power to the ideal output power. At the low photocurrent density, the effect of the series resistance is small enough to be neglected. When $X_S(V_{\text{LC}})$ increases, FF remains the same, but J_{SC} and V_{OC} increases. As a result, P_{out} increases with the incident photon-flux density by a factor of $X \times \{1 + (k_B \times T/q \times V_{\text{OC},1}) \times \ln[X_S(V_{\text{LC}})]\}$, where k_B is Boltzmann's constant (1.38×10^{-23} Joule-K^{-1}), T is temperature in Kelvin, q is the electron charge, and $V_{\text{OC},1}$ denotes the open circuit voltage at $\phi_{\text{input}} = \phi_{\text{onesun}}$ [12]. At the high photocurrent density, the effect of series resistance should be considered. Assume an equivalent series resistance is R_S and the power dissipation can be expressed as $J_{\text{SC}}^2 \times R_S$. Thus the output electrical power density (P_{out}) depending on $X_S(V_{\text{LC}})$ can be expressed as [4]:

$$\begin{aligned} P_{\text{out}}[X_S(V_{\text{LC}})] = {} & X_S(V_{\text{LC}}) \times P_1 \times \{1 + (k_B \times T/q \times V_{\text{OC},1}) \\ & \times \ln[X_S(V_{\text{LC}})]\} - \{[X_S(V_{\text{LC}})]^2 \\ & \times J_{\text{SC},1}^2 \times R_S\} \end{aligned} \tag{3}$$

where P_1 is the ideal output power density under one sun illumination and $J_{\text{SC},1}$ denotes the short circuit current density at $\phi_{\text{input}} = \phi_{\text{onesun}}$. When $X(V_{\text{LC}})$ is a fixed number, $X_S(V_{\text{LC}})$ is a function of sunlight factor (S). Then P_{out} changes with the sunlight factor. However, when $X(V_{\text{LC}})$ is electrically tunable, that means $X(V_{\text{LC}})$ can be adjusted by V_{LC} and then $X_S(V_{\text{LC}})$ can be maintained as a constant no matter how S changes. Therefore, P_{out} can be a constant at different S. That means we can realize a CPV system with a steady electric output by adopting an electrically tunable concentration ratio of the LC lens.

In order to obtain the highest P_{out}, $P_{\text{out}}[X_S(V_{\text{LC}})]$ should satisfy (4)

$$\frac{dP_{\text{out}}[X_S(V_{\text{LC}})]}{dX_S(V_{\text{LC}})} = 0. \tag{4}$$

According to (4), the output power density reaches a maximum when (5) is satisfied.

$$\begin{aligned} & k_B \times T/q \times FF \times \{\ln[X_S(V_{\text{LC}})] + 1\} - 2 \times X_S(V_{\text{LC}}) \\ & \quad \times J_{\text{SC},1} \times R_S + FF \times V_{\text{OC},1} = 0. \end{aligned} \tag{5}$$

The solution of $X_S(V_{\text{LC}})$ in (5) is a fixed number determined by the materials and the structure of the solar cell. Therefore, the LC lens with an electrically switchable concentration ratio can not only help preserving the output power density of the solar cell, but also achieve the maximum output power density of the solar cell.

III. EXPERIMENTAL RESULTS AND DISCUSSION

To demonstrate the concept of the proposed CPV system, we prepared two identical LC lenses [11]. The structure of the LC lens consisted of two indium tin oxide (ITO) glass substrates of thickness 0.5 mm, an LC layer with a thickness of 35 μm, and mechanically buffered poly(vinyl alcohol) layers within anti-parallel directions in order to align LC directors. One of the ITO layers was etched with a hole-pattern within a diameter of 3 mm in order to provide an inhomogeneous electric field to the LC directors. The MLC-2070 nematic LC mixture (Merck, $\Delta n = 0.26$) was used. Two LC lenses are stacked together with orthogonal rubbing directions in order to obtain a polarization-independent LC lens [11].

To measure the concentration ratio of the LC lens, an unpolarized He-Ne laser (Melles Griot, 8144EU for $\lambda = 543.5$ nm) was used. Instead of the solar simulator, here we used the unpolarized He-Ne laser to demonstrate the concept. The

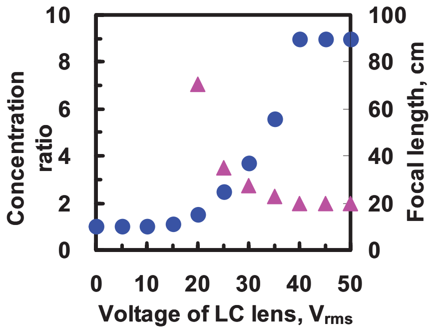

Fig. 2. Concentration ratio (X) of the LC lens (blue dots) and the focal length (pink triangles) as a function of an applied voltage (V_{LC}).

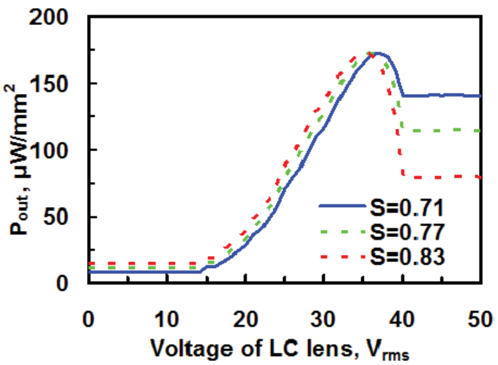

Fig. 3. Output power density as a function of an applied voltage of the LC lens at different S. S represents the ratio of the irradiance of the light source to the irradiance of one sun.

experimental trends by using the solar simulator and the laser are similar [13]. The laser beam was normally impinged to the LC lens because the CPV systems are normally operational under direct sunlight. We then measured the area ratio of the area of incident laser light to the area of the focused light at 20 cm behind the LC lens because the minimum focal length of the LC lens was 20 cm at $V_{LC} > 40V_{rms}$. This area ratio is also the concentration ratio (X) of the LC lens. The concentration ratio (X) of the LC lens and the focal length as a function of the applied voltage (V_{LC}) are shown in Fig. 2. In Fig. 2, the concentration ratio increases from 1 to 9 with the applied voltage when the applied voltage is larger than threshold voltage ($\sim$15 V_{rms}). This is because the distribution of the orientations of LC directors changes with the applied voltage and then results in the smaller focusing spot. The concentration ratio saturates at 9 after $V_{LC} > 40V_{rms}$. This is because the focal length did not change with the applied voltage as $V_{LC} > 40V_{rms}$. Therefore, the maximum concentration ratio of the LC lens is 9.

In order to measure the output power density of the CPV system in Fig. 1(a), the same unpolarized He-Ne laser as a light source impinged to the LC lens and then to the solar cell. The structure of the solar cell was GaInP/GaInAs/Ge triple junction (Arima, Model T3JG6F055011) with a wavelength range: 350–1800 nm and the diameter of 1 mm. The solar cell connected a power supply (Agilent, E3631A) and a multimeter (Agilent, 34401A) was placed 20 cm behind the LC lens. A large area photodiode detector (New Focus, Model 2031) was used to measure irradiance of light. When we applied voltage to the LC lens, we measured the current and the voltage of the solar cell. From the current-voltage curve of the solar cell, we calculated the power of the solar cell as a function of voltage of the solar cell and then found out the maximum power density (i.e. P_{out}) of the solar cell. (The data is not shown here) We then plotted P_{out} as a function of the applied voltage of the LC lens, as shown in Fig. 3. We also changed the irradiance of the light source or sunlight factor (S) by using attenuators to mimic the variation of the weather condition. The S is defined as the ratio of the irradiance of the light source to the irradiance of 1 sun ($\sim$1 mW/mm^2). In Fig. 3 for a fixed S, at $V_{LC} < V_{th}$ LC directors are not reoriented by the electric field, so the concentration ratio or incident number of photons does not change. As a result, the output power density is unchanged. When $V_{th} < V_{LC} <$ 40 V_{rms}, the output power density increases with V_{LC}, reach a maximum and then decreases. This is because LC modulates the incident light and then the concentration ratio or incident number of photons increases with V_{LC}. Thus, the output power density increases as well. However, the power consumption induced by the effect of series resistance increases gradually with an increase of incident number of photons. When the power consumption induced by the effect of series resistance is large enough to compete with the power induced by the photocurrent of the solar cell, the output power density reaches a maximum ($\sim$175 μW/mm^2) at $V_{LC} = V_{max}$ ($<$40 V_{rms}) and then starts to decrease. When $V_{LC} >$ 40 V_{rms}, the concentration ratio or incident number of photons remain the same, the output power density is unchanged. In addition, the output power density increases with S as $V_{LC} < V_{max}$ shown in Fig. 3 because of an increase of the number of photons as S increases. As a result, the output power density varies with S even though V_{LC} is fixed. This also means the output power density of the solar cell under a fixed concentration ratio of LC lens (or typical case of a Fresnel lens) is not a constant, especially the condition of the ambient light changes. As to V_{max}, V_{max} depends on sunlight factor (S). V_{max} is 35 V_{rms} for S = 0.83, 36 V_{rms} for S = 0.77, and 37 V_{rms} for S = 0.71. In fact, the maximum output power density are similar ($\sim$175 μW/mm^2) no matter what kind of sunlight condition is, as shown in Fig. 3. Therefore, according to the result of Fig. 3, we can maintain the maximum output power density of the CPV system by adjusting V_{LC} under different sunlight conditions.

From Fig. 3, we plotted the maximum output power density as a function of sunlight factor (black solid dots) as shown in Fig. 4. The maximum output power density means the output power density at V_{max} in Fig. 3 for a fixed S. According to (3), we also calculated the maximum output power density at different S after considering the experimental parameters: $P_1 = 42.8\ \mu W/mm^2$, $T = 300$ K, $q = 1.6 \times 10^{-19}$ C, $V_{OC,1} = 0.5$ V, $J_{SC,1} = 24$ A/m^2, $R_S = 40$ kΩ, $X_S(V_{LC}) = 4.8$. The calculated results are shown in hollow dots in Fig. 4. As we can see, the experimental results and calculated results of maximum output power density are agreeable. In addition,

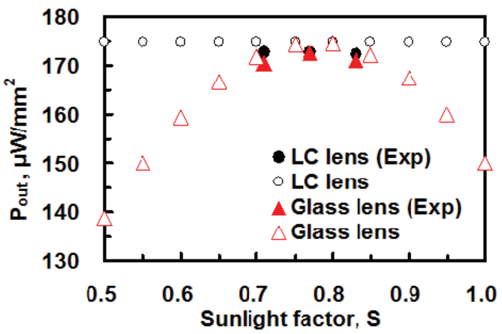

Fig. 4. Maximum output power density as a function of the sunlight factor.

the maximum output power density is almost a constant (~175 μW/mm^2) independent of S. This means we can operate the CPV system at the maximum output power density by adjusting the applied voltage of the LC lens and such output power density does not change even though sunlight conditions changes. In comparison, we also measured the output power density of a CPV system adopting a glass lens whose concentration ratio is fixed (X ~ 6.2) at different S, as shown in the red solid triangles in Fig. 4. The output power density of a CPV system adopting a glass lens changes with S, not a constant. We then calculated the maximum output power density at different S, as shown in hollow red triangles in Fig. 4. The experimental results agree quite well with calculated results.

To compare two CPV systems, the output power density of the CPV systems using the glass lens changes with sunlight conditions; however, the output power density of the CPV systems using the LC lens is not only invariable, but also a maximum in the whole system. Therefore, the CPV system can be utilized at the highest output power density under all kinds of sunlight conditions by using LC lens.

As to the power consumption of the LC lens, the measured current of the LC lens was 0.1 μA and the maximum voltage of the LC lens in the CPV system was 40 V_{rms}. As a result, the power consumption of the LC lens is around 4 μW. The CPV systems using the LC lens can maintain the output power at 137 μW, thus the power consumption of the LC lens can be neglected. To further improve the output power of the CPV system adopting the LC lens, we can reduce the power consumption of the LC lens by reducing the voltage and design new structure of LC lenses and enlarge the diameter of the LC lens in order to enlarge the concentration ratio [8], [11].

The LC lens in Fig. 1 can also be replaced by other polarization independent LC lens, such as blue phase LC lens arrays, polymer-dispersed LC lens arrays etc [8], [11], [14]–[16]. Actually, LC lenses are temperature sensitive devices and the conventional cooling system for the CPV system can help to decrease the temperature factor of LC lenses. Moreover, the dispersion of LC also affects the performance of LC lenses [17]–[19]. Improving the LC materials can reduce the dispersion effect of LC lenses.

IV. CONCLUSION

A CPV system with a steady electrical output adopting an electrically tunable concentration ratio of the LC lens was demonstrated. By controlling the applied voltage of the LC lens in order to adjust the number of incident photons in an area, the CPV system can be operated in the fixed and maximum output power density under different ambient illuminations. The concept of CPV system, in this letter, was not only limited to LC lens, but can also applied to other optical elements whose concentration ratio is tunable, such as liquid lenses, spatial light modulators, and light-induced mechanical stress on a polymer film.

REFERENCES

[1] L. El Chaar, L. A. Lamont, and N. El Zein, "Review of photovoltaic technologies," *Renew. Sustain. Energy Rev.*, vol. 15, pp. 2165–2175, Jan. 2011.

[2] W. T. Xie, Y. J. Dai, R. Z. Wang, and K. Sumathy, "Concentrated solar energy applications using Fresnel lenses: A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 2588–2606, 2011.

[3] M. Dadu, A. Kapoor, and K. N. Tripathi, "Effect of operating current dependent series resistance on the fill factor of a solar cell," *Solar Energy Mater. Solar Cells*, vol. 71, no. 2, pp. 213–218, 2002.

[4] A. Cheknane, H. S. Hilal, J. P. Charles, B. Benyoucef, and G. Campet, "Modelling and simulation of InGaP solar cells under solar concentration: Series resistance measurement and prediction," *Solid State Sci.*, vol. 8, pp. 556–559, Feb. 2006.

[5] P. Peumans and S. R. Forrest, "Very-high-efficiency double-heterostructure copper phthalocyanine/C_{60} photovoltaic cells," *Appl. Phys. Lett.*, vol. 79, no. 1, pp. 126–128, Jul. 2001.

[6] H. K. Kim, M. J. Lee, S. H. Jin, and G. D. Lee, "Optimization of liquid crystal concentration in the dye-sensitized solar cell for high efficiency," *Molecular Cryst. Liq. Cryst.*, vol. 510, no. 1, pp. 323–328, 2009.

[7] J. Schmidt and I. Dierking, "Localization and imaging of local shunts in solar cells using polymer-dispersed liquid crystals," *Progr. Photovolt., Res. Appl.*, vol. 9, pp. 263–271, Mar. 2001.

[8] H. Ren and S. T. Wu, *Introduction to Adaptive Lenses*. West Sussex, U.K.: Wiley, 2012.

[9] S. Sato, "Liquid-crystal lens-cells with variable focal length," *Jpn. J. Appl. Phys.*, vol. 18, no. 9, pp. 1679–1684, Sep. 1979.

[10] H. C. Lin and Y. H. Lin, "An electrically tunable focusing liquid crystal lens with a built-in planar polymeric lens," *Appl. Phys. Lett.*, vol. 98, pp. 083503-1–083503-3, Feb. 2011.

[11] H. C. Lin, M. S. Chen, and Y. H. Lin, "A review of electrically tunable focusing liquid crystal lenses," *Trans. Electr. Electron. Mater.*, vol. 12, no. 6, pp. 234–240, Dec. 2011.

[12] J. Nelson, *The Physics of Solar Cells*. London, U.K.: Imperial College Press, 2003.

[13] Y. Takanashi, K. Takahata, and Y. Muramoto, "Characteristics of InAlAs/InGaAs high-electron-mobility transistors under illumination with modulated light," *IEEE Trans. Electron Devices*, vol. 46, no. 12, pp. 2271–2277, Dec. 1999.

[14] Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, and W. Y. Li, "Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals," *Appl. Phys. Lett.*, vol. 96, pp. 113505-1–113505-3, Mar. 2010.

[15] Y. H. Lin and Y. S. Tsou, "A polarization independent liquid crystal phase modulation adopting surface pinning effect of polymer dispersed liquid crystals," *J. Appl. Phys.*, vol. 110, pp. 114516-1–114516-4, Dec. 2011.

[16] Y. H. Lin, M. S. Chen, W. C. Lin, and Y. S. Tsou, "A polarization-independent liquid crystal phase modulation using polymer-network liquid crystals in a 90° twisted cell," *J. Appl. Phys.*, vol. 112, pp. 024505-1–024505-6, Jul. 2012.

[17] S. T. Wu, "Birefringence dispersions of liquid crystals," *Phys. Rev. A*, vol. 33, pp. 1270–1274, Feb. 1986.

[18] J. Li and S. T. Wu, "Extended Cauchy equations for the refractive indices of liquid crystals," *J. Appl. Phys.*, vol. 95, pp. 896–901, Feb. 2004.

[19] J. Li and S. T. Wu, "Two-coefficient Cauchy model for low birefringence liquid crystals," *J. Appl. Phys.*, vol. 96, pp. 170–174, Jul. 2004.