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ISSN 2737-5323
Volume 4, Issue 1
https://www.iikii.com.sg/journal/AFM
Applied Functional Materials

Article

Laser-Induced Selective Metallization on Polyimide Films for Fabrication of Antennas

Hong-Bing Tsai *, Jui-Ching Lin, Fan-Yu Liao, Yan-Bin Fang, Hung-Ta Wu *

Department of Chemical and Materials Engineering, National Ilan University, Yilan 260007, Taiwan; ljc01589@gmail.com (J.-C. Lin); fanyu890813@gmail.com (F.-Y. Liao); aszx51201@gmail.com (Y.-B. Fang)
* Correspondence: hbtsai@niu.edu.tw (H.-B. Tsai); htwu@niu.edu.tw (H.-T. Wu)

Received: Jan 1, 2024; **Revised:** Feb 5, 2024; **Accepted:** Mar 10, 2024; **Published:** Mar 30, 2024

Abstract: Laser direct structuring (LDS) technology used for polyimide (PI) films containing copper dichromate as the activator for antenna circuits was evaluated. The polyamic solutions containing various contents (1 to 10 phr) of copper dichromate were spread on a glass sheet. Then, the solvent was evaporated and imidated to obtain the PI films containing LDS activator. The near-infrared laser was used to scan the sieving and contrast patterns of the LDS PI films, and then the electrochemical copper was plated. The experiment results indicated that a copper dichromate content of 7 phr exhibited satisfactory quality for the fabrication of the antenna circuits. The comparison results of simulation and measurement from the constructed antenna circuits confirmed that the antenna circuits with the LDS PI film with a width of 50 µm operated appropriately.

Keywords: Laser direct structuring, Polyimide, Laser activation, Electroless copper plating, Antenna circuits

1. Introduction

Laser direct structuring (LDS) technology makes it easy to fabricate electronic parts and products with 3D circuits due to the advanced technology of laser-induced selective metallization [1−4]. Such a part is formed using the method of injection molding where an LDS grade plastic is used as injected material and copper dichromate as an activator. Then, the pulsed laser beam at 1064 nm is adopted to scan a 3D pattern to activate the laser engraved area for subsequent electroless copper plating. Finally, the part is immersed in the plating liquid containing copper to produce a metalized pattern. To obtain sufficient contrast required for applications, it is important to acquire optimum laser activation and electroless plating conditions. Antenna parts and products for mobile devices have been manufactured by the LDS technology [5–7]. Recently, antennas have been fabricated with finer patterns. For compact parts, a flexible printing board on polyimide (PI) is used [8]. LDS technology can be used to make finer patterns due to its finer laser beam size [4, 9]. The combination of these two concepts enables the development of novel LDS PI films and new LDS materials. Generally, PI films are manufactured by a precise coating of polyamic acid solution through the evaporation of solvent and imidation (cyclization) [10−12]. In practice, inorganic activators are incorporated into the polyamic solution. In this research, copper dichromate was mixed thoroughly with plyamic acid which resulted in pyromellitic dianhydride and 4,4'-oxydiphenylamine in N-methyl pyrrolidone. The polyamic solutions containing various contents of copper dichromate were spread on a glass sheet. Then, the solvent was evaporated and imidated to obtain the PI films containing LDS activator. The effects of activator content, activation conditions, and chemical plating conditions were investigated to fabricate antenna circuit patterns on the PI films, and the antenna's performance was assessed.

2. Materials and Methods

2.1. Materials

A plyamic acid solution, PAA Varnish 2SCN, derived from pyromellitic dianhydride and 4,4'-oxydiphenylamine in N-methyl pyrrolidone (NMP) as the solvent, was supplied by Taiflex Scientific Co. Ltd., Taiwan. Copper dichromate was an LD26 grade of Shepherd Technologies, West Chester, USA. The standard solutions for electroless copper plating, ECM-60, were purchased from Teamly Chemicals Corp., Taiwan. The produced chemical copper plating solution included 8.8 g/L of copper sulphate, 6 g/L of sodium hydroxide, 42 g/L of EDTA, 5 g/L of formaldehyde, and 4 mg/L of 2,2'-bipyridine as the stabilizer.

2.2. Preparation of LDS PI Films

A certain amount of copper dichromate powder was added to the plyamic acid solution, and the mixture was stirred thoroughly. The obtained mixture solution was degassed in a vacuum oven at 100°C. Then, the degassed solution was cast on a glass sheet. The oven temperature was controlled from 50 to 175°C at a rate of 50°C/h to dry the coated sheet, and the solvent was evaporated at 175°C for 1 h. Then, the oven temperature was raised to 260°Cand held for 3 h for imide cyclization [13]. The contents of copper dichromate were varied from 0.1 to 10 phr based on polyimide resin to obtain the PI thin films with different copper dichromate contents.

2.3. Laser Activation and Chemical Copper Plating

The standard procedure was used for evaporating the laser activation conditions [3]. Figure 1 shows a sieving pattern used for evaporating laser activation. The LDS PI film was fixed, and a laser machine, BRIMO 20W R2+, supplied by Brimo Technology Co. Ltd., Taiwan was used to scan the PI film. After scanning by the laser, the sample was washed and dried. Finally, the sample was immersed in the plating liquid containing copper for electroless copper plating at 55°C for 15 min. Based on the results of the number of squares with deposited copper metal, the PI film containing 7 phr copper dichromate was chosen for evaluation.

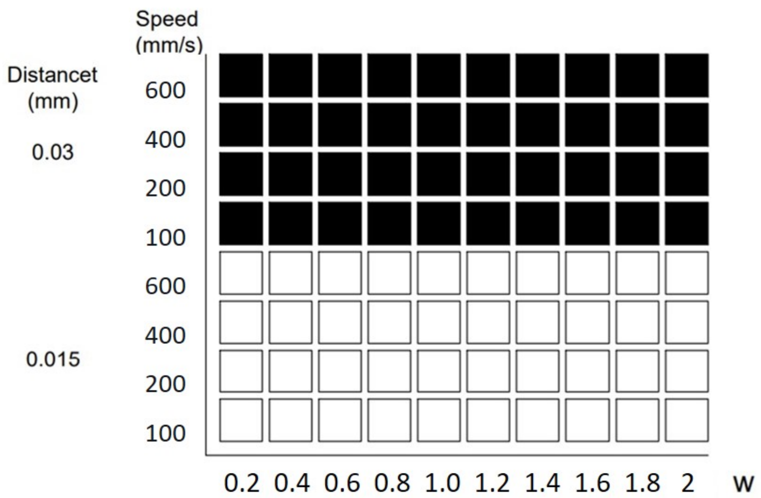


Fig. 1. Sieving pattern for laser activation.

Conditions for the sieving pattern were presented in Figs. 2 and 3. Contrast and line width patterns were analyzed to determine the appropriate laser activation conditions. As a result, the contrast at a laser scanning speed of 600 mm/s and a laser power of 1 W was selected to fabricate antenna circuits.

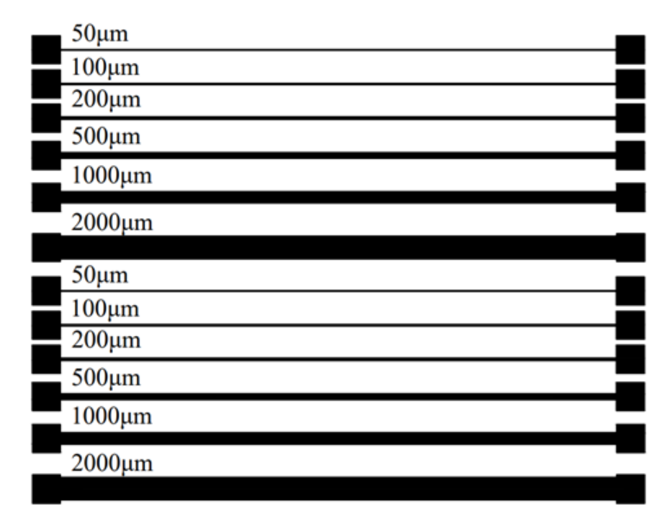


Fig. 2. Contrast pattern.

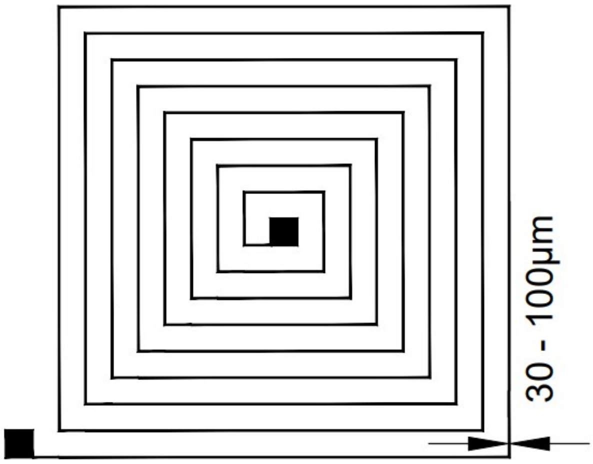


Fig. 3. Line width evaluation pattern.

2.4. Fabrication of Antenna Circuits

A Near Field Communication (NFC) system is composed of readers, tags, and computers on the backend. Most NFC systems employ inductive coupling between a reader and tags. A typical NFC system consists of a transceiver (a reader or a tag) with a coil antenna. The coil function is similar to a voltage transformer. The energy is transferred from readers to tags by magnetically mutual coupling. Communication between tags and readers is completed by load modulation technique. To send data between a reader and a tag, the input impedance of the tag is load-modulated internally. A typical NFC tag consists of a transceiver (a microchip) with a coil antenna (Fig. 4). Variables including coil turns and line width were considered to design the antenna patterns. According to the chosen conditions, the LDS procedure was adopted to fabricate the antenna patterns for depositing square pads on LDS PI films.

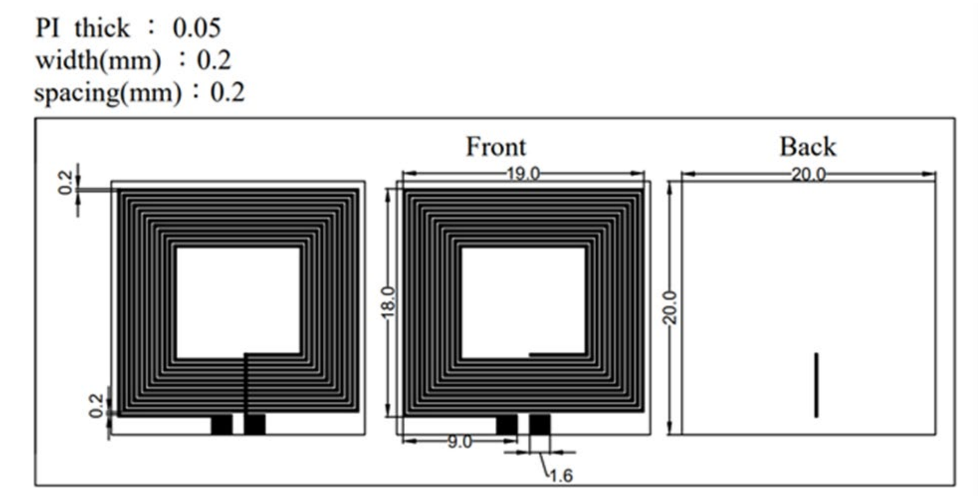


Fig. 4. NFC antenna circuit.

Figure 5 shows the circuit of the NFC tag that consists of a microchip and a spiral antenna. The NFC microchip is symbolized by an equivalent resistor R_S in series with an input capacitor C_S. The spiral antenna can be modeled as a self-inductance L_{ant} of the loop and the resistive loss R_A of the conductor in the higher frequency, such as 13.56 MHz. At resonant frequency, $L_{ant}C_S\omega^2 = 1$, the maximum energy is provided to the tag from the reader antenna, and the total impedance is reduced to $Z_{\text{total}} = R_A + R_S$.

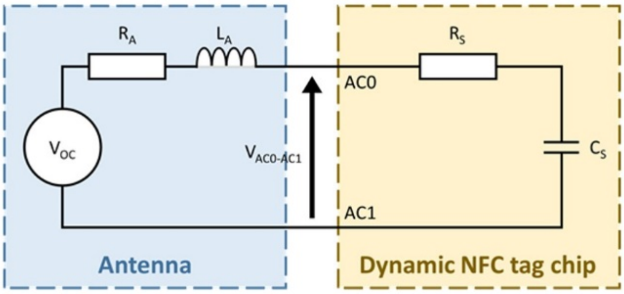


Fig. 5. Equivalent circuit of a NFC tag

A 13.56 MHz antenna can be designed with different shapes. In this research, a square PCB antenna was designed. The dominant parameter of design is its equivalent inductance which must be appropriately designed. Referring to the design guide, the inductance of a square antenna was calculated. The desired inductance value, 2.75 μH was obtained by adjusting and tuning. The final antenna length, strip width, and the number of turns were designed to determine the size of the PCB spiral fabricated on a PI substrate (Fig. 4). The v19.0.0, ANSYS Electromagnetics Suite, is an electromagnetic (EM) simulator developed by ANSYS. The antenna was designed by adjusting geometry and size in the HFSS simulator to meet the conventional specification. Figure 4 shows the simulated antenna circuit with the conventional frequency of 13.56 MHz. The HFSS simulator was adopted to confirm the electrical performance of the designed antenna. Input impedance for the designed antenna was obtained by a network analyzer to check with the simulation results.

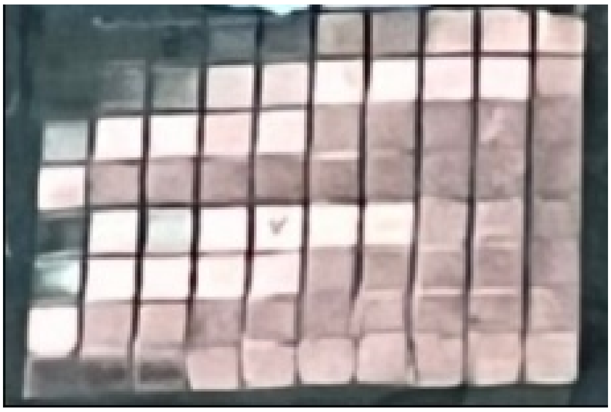
2.5. Fabrication of Antenna Circuits

The IR spectra of the PI films were measured by a Perkin Elmer 1600 series FTIR. The characteristic peaks were at 3320 cm^{-1} (N-H), 2925 cm^{-1} (C-H), 1710 cm^{-1} (C=O), and 1500 cm^{-1} (C=C). Agilent E5071B ENA RF Network Analyzer was used to measure the complex input impedance of the NFC antennas 300 kHz to 8.5 GHz. A VNA with a loop antenna was adopted to measure the resonant frequency of the NFC tag. Connection of the loop antenna to the output of the VNA under reflection mode was conducted to measure Return loss (S11) for the fed port.

3. Results and Discussion

A sieving pattern for laser activation was used to evaluate the activation conditions. The results of the chemical-plated sieving pattern were used to check the content effect of copper dichromate. Figure 6 shows typical results of the chemical plated sieving pattern at various contents of copper dichromate. As the copper dichromate content was below 0.5 phr, no significant amount of copper metal was deposited on the laser-activated area. As the copper dichromate content was 1 phr, several squares showed deposited copper metal. Then, the number of squares with deposited copper metal increased as the copper dichromate content increased. As the copper dichromate content was 5 phr or higher, more than 2/3 of the number of squares with deposited copper was observed, indicating that a content of 5 phr was accessible for laser activation. When the copper dichromate content was 10 phr, the plated LDS PI films showed poor contrast and mechanical properties. Thus, a copper dichromate content of 7 phr was chosen for the fabrication antenna circuits.

(a)



(b)

(c)

Fig. 6. Typical chemical plated sieving patterns: (**a**) 5 phr; (**b**) 7 phr; (**c**) 10 phr.

Appropriate conditions (Fig. 6 (b)) were selected for creating the contrast pattern to evaluate the maximum laser activation condition. The laser activation conditions in Fig.7 were at a laser scanning speed of 600 mm/s, a point distance of 0.015 mm, and a laser power of 1 W with a pulse frequency of 40 kHz. Since the contrast under these conditions was appropriate, the laser condition was chosen for the fabrication of the circuits. Although better conditions are possible, the activation condition under the selected laser conditions showed sufficient quality for antenna circuit fabrication. The LDS procedure was adopted to fabricate the patterns. The patterns were evaluated as shown in Fig. 8. The line width of 30−50 µm was used for designing antenna circuits.

Fig. 7. Metallized contrast pattern.

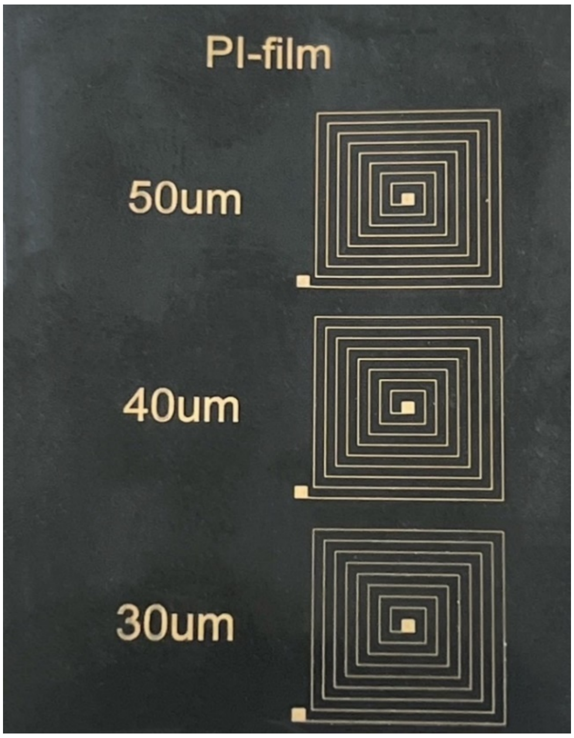
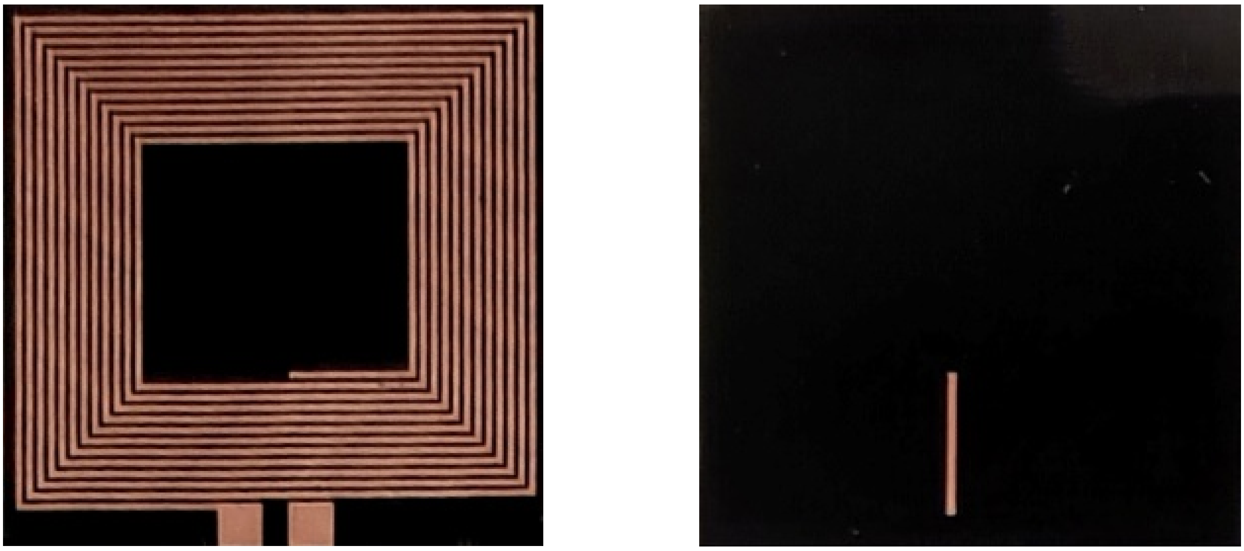


Fig. 8. Metallized Fine line evaluation.

Figure 9 shows the PI antenna circuit with a line width of 200 μm fabricated by the method of LDS procedures. The right pad and inner terminal of the front side were connected through the line of the back side and metalized walls which were formed by the laser scanning method. The resistance between these two pads was less than 10 Ω.



(a) (b)

Fig. 9. Photographs of NFC antenna on LDS PI., (**a**) front side, (**b**) back side.

The complex input impedance of the NFC antennas was measured by the HP 5071 B vector network analyzer and then compared with the simulation results. The tag antenna was measured by a test fixture with a port extension technique for calibration, and then its impedance was measured, too. The comparison result of the measured input impedance of the tag antenna with the simulated results by HFSS is shown in Fig. 10. The fabrication process for the designed antenna was stable and acceptable.

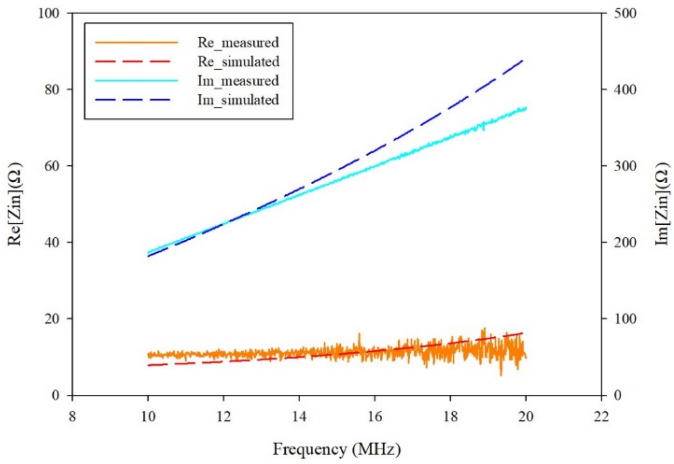


Fig. 10. Measured input impedance of the NFC tag antenna compared with the simulated results.

A vector network analyzer (VNA) with a loop antenna was used to measure the resonant frequency of the NFC tag. Measurement of S11 from the fed port whose loop antenna was connected to the output of the VNA, was performed in reflection mode. At resonance, the resistance of the loop probe impedance reached the maximum value while the reactance was zero. The input impedance of the loop probe was 50 Ω, which was the minimum value in the reflection mode. Figure 11 shows the experiment for measurement. Figure 12 shows the measured reflection coefficient S11 versus frequencies. The tag resonated at 13.64 MHz. The difference between the experimental and simulated results was caused by the location of the circuit. The operation of the fabricated antenna circuits on LDS PI films was stable in its function.

Fig. 11. Experiment setup of measured resonant frequency of NFC tag.

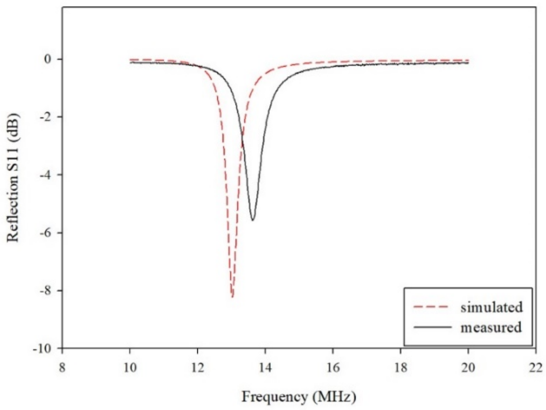


Fig. 12. S11 versus frequency curves of the NFC tag, experimented at 13.05 and 13.64 MHz.

An NFC chip, NTAG216F, from NXP Semiconductors N.V., Netherlands was used to evaluate the function of the antenna circuits. The two pins of the NFC chip (NTAG216F) were in contact with the pads of the LDS PI antenna. The antenna system was accessed by using a 5G mobile phone (Samsung S21). An APP, NFC Tag Writer by NXP, was downloaded for an access test. The URL of National Ilan University was used. When the mobile phone was within 5 cm of the antenna system, the website of National Ilan University was displayed on the screen as shown in Fig. 13. This demonstrated that the LDS PI antenna performed its transmission function.

Fig. 13. Samsung S21 5G model with NFC antenna system showing the website of National Ilan University.

4. Conclusions

PI films containing the LDS activator were prepared in this research. Different patterns for sieving, contrast, and line widths were applied to the PI films by near IR laser system. After activation, the PI samples were dipped in the electroless copper plating solution for chemical copper plating. The results showed that a copper dichromate content of 7 phr exhibited satisfactory operation. so was chosen for the fabrication of the antenna circuits. Coil antenna circuits for the NFC system were fabricated on the LDS PI film. The operation result of the circuit correlated well with that of the simulation. Therefore, the LDS PI films can be used as the antenna circuits with a fine width of 50 µm.

Author Contributions: conceptualization, H.-B. Tsai; methodology, H.-B. Tsai; validation, H.-B. Tsai and J.-C. Lin; formal analysis, F.-Y. Liao; investigation, Y.-B. Fang and H.-T. Wu; resources, H.-B. Tsai; data curation, J.-C. Lin; writing—original draft preparation, H.-B. Tsai; writing—review and editing, F.-Y. Liao and H.-T. Wu; visualization, H.-T. Wu; supervision, H.-B. Tsai.

Funding: This research did not receive external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank AR Display Co. Ltd., Taiwan for the financial and technical support of this work.

Conflicts of Interest: The authors declare no conflict of interest**.**

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