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Inkjet-printed silver film on multilayer liquid crystal polymer for fabricating a miniature stub-loaded bandpass filter

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ABSTRACT

In this study, the mechanical properties of silver film are studied using a nanoindentation test, dynamic bending test, and lamination bonding pressure test. The hardness and elastic modulus of silver film were approximately 1.08 and 88.5 GPa, respectively, which corresponds to those of bulk silver. Acceptable fatigue properties were obtained after 10^4 dynamic bending cycles. A lamination bonding pressure of 0.69 MPa and temperature of 270 °C were used to achieve multilayer liquid crystal polymer (LCP) technology. A miniature bandpass filter using inkjet printing technology on multilayer LCP was realized with a minimal S_{21} value of −1.4 dB at 25 GHz. The results demonstrated the proposed design methodology and fabrication technique.

1. Introduction

With the rapid development of portable electronic devices, flexible electronic system package technology has been developed for the production of wearable electronics and for flexible display applications. Emerging system-in-package and three-dimensional (3D) integration technologies [1–4] are the predominant providers of solutions for miniaturizing systemized radio frequency or millimeter wave devices. Previous research [5] reported the development of an inkjet-printed folded-bowtie *radio frequency identification* tag module on a paper substrate. In [6], an inkjet-printed three-stage slotted-patch bandpass filter on multilayer paper substrates was presented for wireless local area network applications. Although paper was shown to be an effective substrate that offers low cost, as well as fast and simple inkjet printing; however, its application remains limited because of issues related to high frequency, absorptivity, and humidity issues. That study also presented a dual-band filter on a liquid crystal polymer (LCP) substrate and an antenna on multilayer LCP substrates. LCPs have recently been recognized as a favorable material for high-frequency applications, exhibiting a stable dielectric constant, an impressive loss tangent, favorable moisture absorption, low thermal expansion coefficient, and multilayer design capabilities [7–9]. Studies [10,11] have demonstrated that employing inkjet printing technology for fabricating LCP substrates. Moreover, inkjet-printed technology is faster and more economical than using additive manufacturing technologies [5,6,12,13]. The technologies can be used to give flexible properties to a flat, curved, or dynamic surface. However, the mechanical properties of silver film are essential to flexible electronic applications [12,13]. The strength of silver film should be examined at room temperature after lamination bonding process because the multilayer lamination bonding process is performed at high-temperatures and in high-pressure environments. Therefore, the mechanical properties, including nanoindentation and bending effect, of silver film on an LCP substrate should be studied. The lamination bonding conditions of multilayer LCP technology should also be established to achieve a compact size. The results of this study show that the hardness of inkjet-printed silver film is approximately 1.08 GPa by nanoindentation measurement. Only 0.1 dB degradation of S_{21} of a silver line was obtained after 10^4 bending cycles. The optimal lamination bonding pressure of 0.69 MPa was used to fabricate multilayer LCPs to achieve appropriate level of adhesiveness, and no cracking was observed on the surface of the silver film. According to the mechanical property results, a bandpass filter was realized using multilayer LCP technology to achieve a compact size and acceptable performance. The multilayer LCP technology is suitable for portable and flexible electronic applications.

2. Experiments

Fig. 1 shows the inkjet printing and lamination bonding process flow. The metal layers were fabricated using silver ink (DGP-40LT-15C, Advanced Nano Products Co., Ltd.) with inkjet-printing technology (Dimatix DMP-2800, Fujifilm, USA). LCP substrates are generally divided into two types: core films and bonding films. ULTRALM 3850 liquid crystalline polymer core film and ULTRALAM 3908 bonding film (Rogers Corporation) were used as the main substrate (thickness, 100 μm) and

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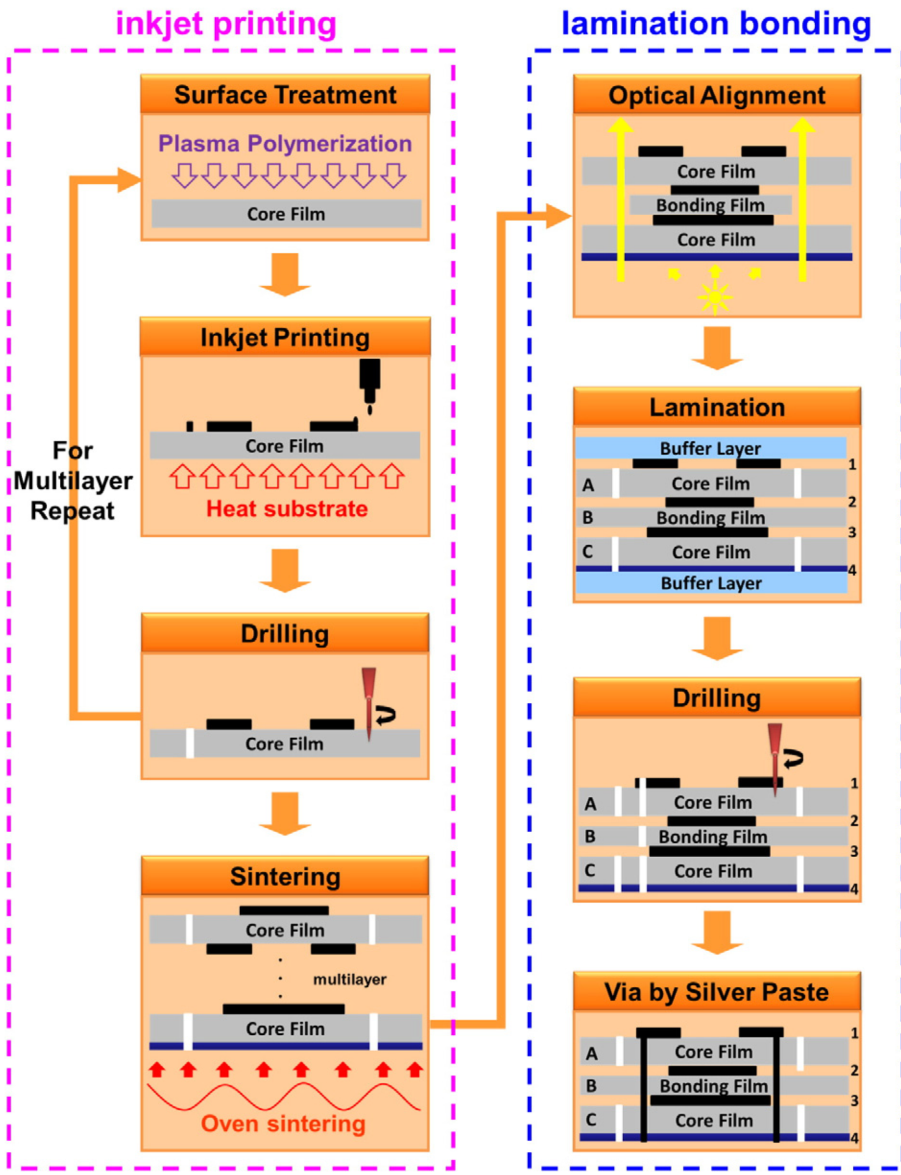

Fig. 1. Inkjet printing and lamination bonding process flow.

adhesive layer (thickness, 50 μm), respectively, because according to the manufacturer datasheets they exhibit similar characteristics, such as their thermal expansion and dielectric constants. Silver film was printed onto an LCP substrate to form a metal layer and multilayer LCP lamination bonding process under the following conditions [10]: 1) a 3-W, 5-s plasma polymerization surface treatment was applied. 2) The silver ink was printed onto a core film at 60 °C. The layout of each core film was inkjet-printed independently. The silver film was formed as a double-sided layer for Layer A (No. 1, 2) and a one-sided layer for Layer C (No. 3). Another size of layer C is copper (No. 4) as a ground plane for microstrip measurement. 3) A hole was drilled in the core films (Layers A and C) to enable optical alignment. 4) The silver film was post-baked at 270 °C for 1 h by using a 10-pass printing process. The sintering temperature of silver (270 °C) was used to sufficiently cure the nanoparticle silver ink because high conductivity is required for applications in the gigahertz frequency range. The bulk silver conductivity and thickness were approximately 1.2 to 2.0 × 10^7 Siemens/m and 3.0 to 3.6 μm, respectively. 5) Each LCP core film was aligned using an optical alignment and bonded to the laminate by using a bonding film (Layer B). 6) High pressures and high temperatures are required during the lamination bonding process. The buffer layers were used at the top and bottom to protect the silver film, LCP, and ground plane. The melting point of 3850 LCP and 3908 bondply is 315 °C and 280 °C, respectively. The bonding temperature and pressure are the resulting tradeoff of the lamination process. However, the LCP become brown at a bonding temperature of 280 °C. Therefore, the bonding temperature was set at 270 °C. The temperature was increased incrementally by approximately 3.5 °C/min from room temperature to 270 °C and then cooled to room temperature while maintaining constant pressure. This process prevented registration errors between the upper and lower layers. Various lamination bonding pressures were studied. 7) A ground pad was used to drill a hole using a drilling machine fitted with needle with a 0.2 mm diameter; and 8) the hole was filled with a silver paste to connect the back ground plane for radio frequency measurement.

The mechanical properties of the silver film were characterized using a nanoindentation test, impact test, dynamic bending test, and lamination bonding pressure test. The nanoindentation test was performed using a TriboIndenter (Hysitron Inc., TI 900). The dynamic bending test and lamination bonding pressure test were used to measure the S-parameters of the silver line. The S-parameters of the silver line and filter were measured using an HP E8364C network analyzer. The surface morphologies of silver film exposed to lamination bonding