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Rapid and high-performance processing technology for large-area frequency selective surfaces

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A R T I C L E I N F O

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A B S T R A C T

Frequency selective surfaces (FSSs) with periodic smart structures have widespread applications in many areas, especially in electromagnetic wave filters. In this paper, a rapid and high-performance processing technology for large-area FSSs was presented. This novel technology combined laser direct writing lithography (LDWL) with wet chemical etching (WCE) (i.e., LDWL + WCE). Basing on experiments and in the condition of optimal parameters (i.e., 40 mW laser power, 1000 mm/s scan speed, single scan, 20 µm hatch space, pattern-profile scan path, and ferric chloride aqueous solution as etchant) of LDWL + WCE, a large-area (200 × 200 mm^2) aperture type FSS with 625 square-loop units was fabricated within 8 min on a FR-4 copper-clad plate (with 12 µm-thickness copper layer). When the same FSS was prepared by commonly-used laser direct ablation (LDA) technology with itself optimal processing parameters, it needed about 62 min (nearly 8 times as much time as the former). Scanning electron microscopy (SEM) and surface probe profilometry analyses showed that the edges of the square-loop patterns fabricated by LDWL + WCE were steeper and smoother, and the FR-4 substrate had no damage. In an anechoic chamber, the electromagnetic wave filtering performances of the as-prepared FSSs were tested, and the results indicated that the FSS fabricated by LDWL + WCE had a bandpass response at 7.08 GHz with a transmittance of 97.75%. Its frequency response curve was in better agreement with the simulation result. The technology of LDWL + WCE also has the potential to rapidly fabricate large-area and/or non-planar FSSs with high performance.

1. Introduction

Frequency selective surfaces (FSSs) with periodic smart structures are generally composed of conductive patches or aperture elements within a metallic screen (the screen was usually supported by a dielectric substrate) (Munk, 2005). They are designed and used to transmit, absorb, or reflect electromagnetic waves at certain frequencies. Thus, they have been widely used in such areas as radar cross section (RCS) reduction (Kim et al., 2008a,b), electromagnetic shielding (Rahman et al., 1995), microwave absorption (Wei et al., 2009), structural health monitoring (Sang-Dong et al., 2013), wireless communication (Yong et al., 2018), antenna design (Hong-Kyu et al., 2011), optical signal filtration (Lu et al., 2016), and so on.

Accordingly, a great attention has been paid to the fabrication of FSSs. In the open literatures, commonly-used FSS fabrication technologies include standard contact/projection photolithography (Moallem and Sarabandi, 2012), inkjet printing (Cooper et al., 2012), screen printing (Li et al., 2017), micro-pen dispensing (Marhefka et al., 2007), e-beam evaporation (Kim et al., 2014). For example, Kim et al. (2008a,b) fabricated stealth radome with FSS using standard photolithography. Batchelor et al. (2009) demonstrated inkjet printing as a facile digital fabrication tool for the manufacture of FSS. Liu and Kim (2016) manufactured a square loop FSS for wide-bandwidth microwave absorber by screen printing. Marhefka et al. (2007) fabricated an FSS antenna ground plane using micro-pen dispensing. Kim et al. (2014) proposed a composite FSS fabricated by an e-beam evaporator.

However, the above processing technologies usually have their self-drawbacks. For example, standard contact/projection photolithography usually requires a mask and then projects the mask pattern to a photoresist-coated substrate (Pease and Chou, 2008). This technology is able to achieve high line/space resolution, but it has less process flexibility, longer production cycle, more cost, and more difficulty for large-area and/or non-planar FSSs. Inkjet printing is a rapid and non-contact pattern-printing technology by directly depositing conductive droplets

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(e.g., silver ink) on substrates. Whereas, it is a more-defect and less-precision patterning technology (Song and Nur, 2004). Screen printing is a stencil-based process, and it needs to pre-fabricate a stencil with designed patterns, and then squeezes the ink through open areas of the screen mesh onto the printing substrate (Novaković et al., 2016). Thus, this technology is lack of flexibility and wastes ink. Micro-pen dispensing is an additive mask-free patterning technology (Lewis and Gratson, 2004). But it has a critical demand for the substrate surface flatness, and is low-efficiency because of the low-speed movement of mechanical stages. E-beam evaporation needs a specially-designed mold and a vacuum chamber to make FSS patterns (Bishop, 2015). This technology is also more-defect and lower-efficiency.

Over the past decade, laser direct ablation (LDA) technology has been developed rapidly. It utilizes a focused laser beam to directly ablate material layers and to produce patterns on substrates. Thus, this is a non-contact, maskless and flexible patterning technology (Hon et al., 2008), and it could be used to fabricate high-resolution patterns in small areas (Mizeikis et al., 2010). When LDA is used to fabricate large-area FSSs, in order to directly ablate the metal (e.g., copper or aluminum) layer on a substrate, it usually needs high laser power and very low scan speed (Li et al., 2018). This not only reduces the processing efficiency, but also inevitably damages the dielectric substrate frequently.

In this paper, a novel fabrication technology for large-area FSS was proposed. It combined laser direct writing lithography (LDWL) with wet chemical etching (WCE) (i.e., LDWL + WCE). It utilized a focused laser beam to directly expose the photosensitive material (e.g., photoresist) coated on a substrate. After development and wet chemical etching, the patterns were transferred onto the substrate. Because of the very low exposure energy threshold of the photoresist, the demand laser power was very low. Meanwhile, the laser beam scan speed depending on a galvanometer scanner could be elevated greatly. Thus, this was a maskless, flexible, rapid, non-contact processing technology. As a comparison, LDA technology was also adopted.

2. Experiment section

2.1. Material

Commercially available FR-4 copper-clad plates (FCCP) were purchased from Shenzhen Haiqunli New Material Technology Co., Ltd (Shenzhen, China). The plates were cut into 200 mm × 200 mm in size (length × width), the copper layer was about 12 μm thick, and the FR-4 dielectric substrate was about 1 mm thick. Commercially available positive photoresist SUN-110 P and developer SUN-238D from Suntific Materials CO. Ltd (Weifang, China) were used in the experiment. The photoresist was a diazonaphthoquinone (DNQ) positive photoresist and the developer was mainly composed of tetramethylammonium hydroxide (TMAH). Self-prepared wet chemical etchant was 50 *wt.* % ferric chloride ($FeCl_3$) aqueous solution.

2.2. Experimental methods

Fig. 1 was the schematic diagram of LDWL or LDA equipment system. The both systems included a laser source, an optical system, and an x-y-z three-dimensional (3D) translation stage, respectively. For LDWL, the laser source was with a wavelength of 355 nm and a maximum output power of 0.5 W; For LDA, the laser source was with a wavelength of 1064 nm and a maximum output power of 20 W. The focused laser spot diameters at $1/e^2$ of their maximum intensity were approximately 10 μm and 20 μm, respectively. In either optical system, a beam expander was used to expand and collimate the laser beam and a high-speed galvanometer scanner was used to rapidly manipulate the laser beam, and the optical deflection angle range was between -20° and +20°; Besides, an F-theta lens was used to focus the laser beam on a plane. The both translation stages had movement ranges of 200 mm in

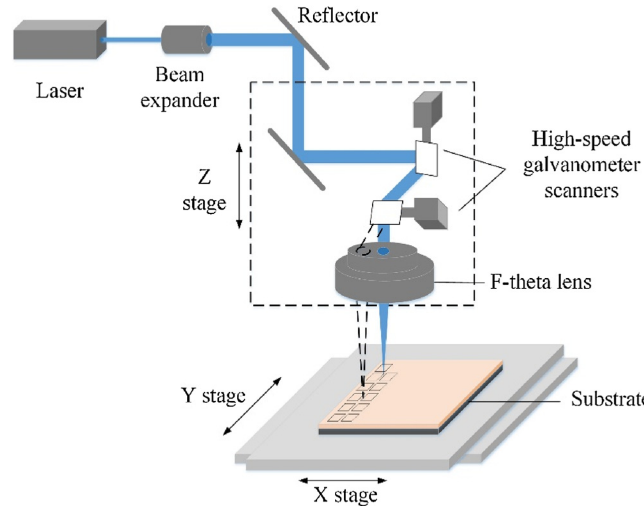

Fig. 1. Schematic diagram of LDWL or LDA equipment system.

both x and y directions, and the both z stage could carry the galvanometer scanner and F-theta lens moving up and down in a range of ± 25 mm (larger movement ranges meant larger processing areas or volumes). These made the systems have the potential for larger-area, non-planar and/or 3D fabrication.

For LDWL + WCE, the processing procedures were shown in Fig. 2. First, the FCCP was coated with the above-mentioned photoresist layer. After baking on a hot plate under 100 ℃ for 1 min, using the above LDWL equipment system, it was directly written the pre-designed patterns on the photoresist. Next, it was developed in the developer solution. And then, it was implemented a wet-etching process in the above-mentioned $FeCl_3$ aqueous solution. Finally, the residual photoresist was washed away in acetone.

2.3. Measurements and characterization

The microstructures of the as-prepared FSSs were observed using a sirion200 scanning electron microscope after the samples were sputter-coated with gold. The surface profiles of the substrate after WCE or LDA were measured by a KLA TencorP-16+ surface probe profiler. Electromagnetic wave characteristics were tested and evaluated in a microwave anechoic chamber using a free-space measurement setup (Fig. 3). Two waveguide horn antennas sweeping among a frequency range of from 2 GHz to18 GHz were connected to a signal source, and they were placed 1 m away from each side of the FSSs. The data simulation of electromagnetic wave characteristics was accomplished using a commercially available software named High Frequency Structure Simulator (HFSS).

3. Results and discussion

3.1. Structure of FSSs

Generally speaking, FSSs are composed of the periodic structures containing such self-symmetric patterns as circular rings, square loops, dipole, etc. because of the good stability of these patterns (Panwar and Lee, 2017). Depending on corresponding demand, FSS can be designed and fabricated on a planar or curved surface, and the adopted materials can be pure conductors (e.g., metal) or composite materials consisting of conductive layers and dielectric layers.

In our experiments, square loop was chosen as the periodic pattern unit of FSS, and FCCP was used as the fabrication material. Fig. 4 was the structure of a FSS. Its whole size was 200 mm × 200 mm, and it had 625 square loop periodic units. The geometry of each unit was: p = 8 mm, a = 7.05 mm, b = 6.45 mm and loop gap g = 300 μm. The