Microelectronic Engineering 168 (2017) 10–14

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Accelerated publication

# Fractal inductors on flexible plastic substrate fabricated by laser ablation

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ARTICLE INFO

*Article history:*
Received 17 August 2016
Received in revised form 30 September 2016
Accepted 16 October 2016
Available online 18 October 2016

*Keywords:*
Inductors
Fractal design
Flexible substrate
High frequency
Laser ablation

ABSTRACT

In this paper, the feasibility of laser ablated inductors of fractal design on flexible plastic substrate is demonstrated. Inductors are used to store energy during each switching cycle in a switching voltage regulator circuit. Sierpinski fractal inductors of the second and the third iteration were designed, fabricated, and characterized. Two conductive materials, commercially available, were investigated – copper and aluminium adhesive tapes. The inductors are ablated with a current of 28.5 A, a frequency of 50 kHz and a speed of 1000 mm/s in five passes. High frequency parameters as inductance, quality factor, and resistance were analyzed. The inductors were characterized in the frequency range from 10 kHz to 1 GHz. Copper inductors showed better performances than aluminium inductors.

## 1. Introduction

To meet the urgent demands of ever-increasing number of applications, the simultaneous improvement in device technology and miniaturization are necessary. Wearable devices are moving quickly from concept to reality based on sensor fusion, communications, and vision. However, the design and development of wearable devices is not only making use of existing technologies, but also prompting the development and evolution of others. Wearable devices require ever-smaller components, lower power consumption, flexibility, and low cost. These systems utilize increasing numbers of power modules, which occupy a major part of system volume. Therefore, the most critical part is to design interface to control power supply. One of the component, which limits flexibility and miniaturization of these systems, are inductors. Tremendous efforts have been made to develop cost effective and high quality inductors.

Although the spiral inductor is used for a wide range of applications, it requires at least two layers or an air bridge to be used in a system, thus not being suitable for low-cost circuits. Low-cost circuits require planar single-layer structures. Besides spiral design, common inductor designs are the hoop and the meander, as well. These designs are single-layer structures. In the hoop, the flux path is widely spreading, while in the meander, the flux path is restricted in narrow channels. Therefore, the meander type inductors will have better frequency characteristics than the hoop type [1]. One of the main problems when it comes to designing planar inductors is the surface area. Planar inductive structures do not couple magnetically well. This problem could be improved through fractalization.

Fractal curves have space filling properties, depending on iteration, while the arrangement still occupies almost the same space. In addition, fractal inductors are quite suitable for application in wearable electronics (stretchability and flexibility), because a tortuous path relives mechanical stress and creates a more compliant structure. Fractals are composed of periodic kinks, due to these complex curves are more compliant and able to undergo larger strains without reaching the yield strength of the metal [2]. Fractal curves are widely used in antenna design [3,4], capacitors design [5,6] and sensors [7,8], as well. Furthermore, fractal-based layouts create new design opportunities in stretchable electronics, including a broad range of devices suitable for biomedical systems [9]. A controlled way of generating fractal electricity in which novel electronic devices feature a fractal distribution of conducting channels is proposed in [10].

Comprehensive study of fractal microinductors has been given in [2]. Fractal Koch inductors on flexible substrate were reported in [11]. Planar inductors with conductive pathways oriented in a fractal loop-based layout were analyzed in [12]. Fractal inductors based on fractal Hilbert curve pattern were described in [13–16].

When it comes to fabrication of low-cost flexible inductors for application in wearable electronics, there are several attractive techniques. Ink-jet printing has been fashioned as a challenging and attractive non-contact fabrication technique due to its high throughput and low cost. The feasibility of ink-jet printed passive components is demonstrated in [11,17]. Ink-jet printed multilayer inductors with through vias are reported in [18]. High quality factor, meander inductors are demonstrated utilizing ink-jet printing on organic paper substrate [19]. Another example of reduced cost and increased throughput of flexible electronic applications is screen printing [20]. Screen-printed

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http://dx.doi.org/10.1016/j.mee.2016.10.008

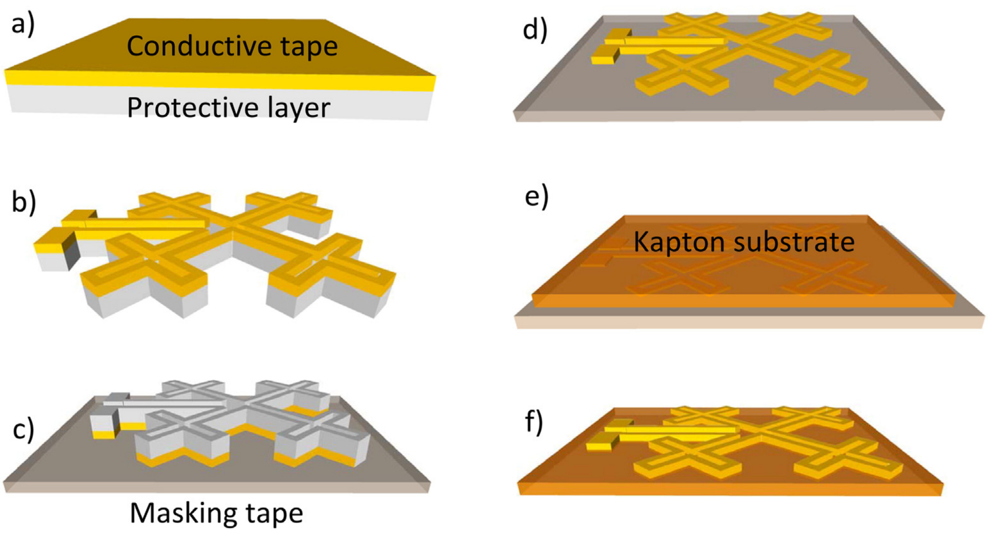

**Fig. 1.** The process sequence of inductors fabrication: a) conductive adhesive tape (copper and aluminium), b) laser ablation of the conductive tape and protective layer, c) transfer of the conductive layer to the masking tape, d) removal of the protective layer, e) transfer of the adhesive conductive tape on Kapton substrate, f) lift-off of the masking tape.

inductors in the μH range to achieve minimal series resistance and high performance at frequencies relevant to power electronics is reported in [21]. Shadow mask technology is gaining impetus as another alternative micropatterning technique [22]. Laser ablation through the laser direct writing technique meets demands of low-cost flexible components, as well. Planar square inductor was fabricated on a copper-coated glass substrate using the laser ablation process [23]. In [24], ITO films on glass substrate were patterned into spiral inductors by laser ablation. Laser direct writing of co-planar waveguides on flexible substrate has been reported in [25].

In this paper, performance analysis of inductors fabricated on the plastic substrate by laser ablation is demonstrated. Conductive adhesive tapes were patterned by laser ablation and deposited on the flexible polyimide substrate. Inductors are of Sierpinski fractal designs. Sierpinski inductors of the second and the third iteration were analyzed. This fractal type forms a complete curve, beginning and ending at approximately the same location, which simplifies characterization. The objective of this paper is to demonstrate the feasibility of the flexible fractal inductors fabricated in low-cost and environmentally friendly manner for application in wearable electronics.

## 2. Inductors design and fabrication

Sierpinski fractal inductors were tested: the second and the third iteration of Sierpinski curve. Active area of the second iteration of the inductor is 21.1 mm × 21.1 mm, whereas the active area of the third iteration of the inductor is 20.7 mm × 20.7 mm. Inductors of the second and the third iteration occupy approximately the same space. Line width is 0.6 mm for both designs. Sierpinski fractal curves were rotated for 90° in order to cover square surface area. Kapton polyimide film of 75 μm thickness was used as the flexible substrate. Two conductive materials were investigated for the fabrication of the flexible fractal inductors: a copper (Cu) and an aluminium (Al) adhesive tape of 35 μm thickness. Commercially available Cu and Al adhesive tapes have been chosen for fabrication of the inductors as a compromise between the cost and low resistance of materials. A laser ablation process (Diode pumped Laser Rofin Powerline D, ND: YAG, 1064 nm) was used for shaping and cutting the geometries necessary to implement fractal lines for both materials, thus resulting in a cost-effective, mask-less, time-saving and environmentally friendly fabrication process. The process sequence is illustrated in Fig. 1.

All inductors (Fig. 1a) were ablated with a current of 28.5 A, a frequency of 50 kHz and a speed of 1000 mm/s. Five passes were needed to completely ablate the conductive tape and the protective layer, as it is shown in Fig. 1b. In the next step, the non-adhesive side of the conducting tape was attached onto a low tack masking tape used as a sacrificial layer, shown in Fig. 1c, and the protection layer was removed, shown in Fig. 1d. Afterwards, the adhesive side of the tapes was transferred on the flexible substrate (Fig. 1e) as a tattoo and the masking tape was manually lifted off, as shown in Fig. 1f. Using this method, the fast fabrication of the fractal inductors on the flexible substrate was successfully achieved, as it is in Fig. 2. This method is especially suited for passive components because of large conductive tape thickness (35 μm), which is necessary to minimize series resistance of metallic

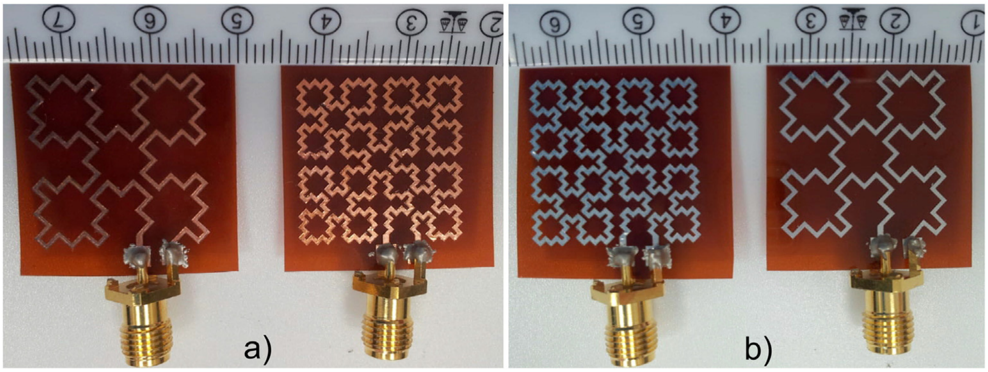

**Fig. 2.** Fabricated inductors: a) the second and the third iteration of the Cu inductors, b) the second and the third iteration of Al inductors.