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A miniaturized Rogowski current transducer with wide bandwidth and fast response

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Abstract
The miniaturization of the 3D Rogowski current transducer down to the micro-scale is essential for device integration and expansion of its application scope, particularly for ‘lab-on-a-chip’ systems. However, fabrication of 3D miniaturized Rogowski coils remains challenging as most relative methods still rely on the 2D micromachining process. In this paper, a miniaturized Rogowski coil current transducer was fabricated using an improved femtosecond laser wet etching technology and a metal microsolidification process, in which a metal alloy with a relatively high melting point was used and a robust but simple packaging structure based on a conical electrode was developed. The results show that the miniaturized Rogowski coil current transducer reveals a response time of less than 1 ns, high sensitivity and good detection capability for high-frequency electrical signals. The miniaturized Rogowski coil can easily be integrated into functional microsystems and will be widely applicable for high-frequency electric signal detection and circuit protection.

Keywords: current transducer, femtosecond laser, wide operation bandwidth

1. Introduction

The demand for high-performance electronic-sensitive detectors has increased significantly because of their potential use in microcircuits and electronic interconnections in the fields of broadband communications, medical testing and security monitoring [1–3]. Various types of coil forms have been studied and applied to electric current detection. For example, the Rogowski coil has been recognized as an ideal electrical device for measuring the alternating current (AC) or high-speed current pulses. Typical applications of the Rogowski coil include use in short-circuit testing of electric generators and as protection sensors for electrical plants [4, 5].

The Rogowski coil, which consists of toroidal form windings which encircling the current path, is a kind of air-core coil, which means it does not contain a ferromagnetic core. Its special structure gives it advantages over other types of current transformers, including a faster response speed, better linearity, and a wider operating bandwidth. The study of Rogowski coils has thus remained a hot research topic for decades. Recently, Samimi et al reviewed the studies of Rogowski coils and the advancements made in these coils over the last decade [6].

While Rogowski coils have excellent electric properties for use in AC and impulse-detection applications, they are not suitable for application to integrated ‘lab-on-a-chip’ systems, due to the comparatively large scale of these devices and their narrow operating bandwidths. Current transducers based on the Rogowski coil are often more than 10 cm in size, and their operating bandwidths have generally been limited to about dozens of megahertz [7]. There is, therefore, an unfulfilled demand for the broadening of the Rogowski coil’s operating bandwidth to the levels of hundreds of gigahertz (GHz) or terahertz (THz) and promotion of its application in integrated circuit, micro-electro-mechanical and other micro-functional systems [8–10]. To meet such a demand, new fabrication technologies that can miniaturize these complex three-dimensional (3D) coils to the micro-scale have become necessary.
Several techniques have been studied for the fabrication of complex structures based on many types of materials in recent years [11–13]. However, the resulting planar microcoils have inhomogeneous magnetic fields and low inductance values. The device bandwidth is limited, and its response speed is slower than that of a conventional device. The fabrication of a smooth conductive bulk 3D Rogowski coil structure also remains technically challenging. In our previous studies [14, 15], we proposed the fabrication of complex 3D microcoils in fused silica using a femtosecond laser wet etch (FLWE) technology and a metal microsolidification process. This single-microcoil fabrication method provides new ideas for and solutions to the problems of processing of workable miniaturized 3D Rogowski coils in fused silica. Based on this approach, it will be possible for the miniaturized coil to be integrated with other microfluidic devices for micro total analysis system (μTAS) applications.

When compared with the single microcoil process, the low melting point of the metal in the microsolidification process is a limiting factor for the application of the device. The low melting point metal cannot support relatively high currents, which means that the microcoil circuit will break down easily. Additionally, a typical 3D Rogowski coil consists of a helical coil of wire with the lead from one end returning through the center of the coil to the other end, such that both terminals are at the same end of the coil [16]. Because the Rogowski coil was embedded in the fused silica chip, a central through-hole was designed to fit the input wire. Therefore, a glass-polydimethylsiloxane (PDMS)-electrode structure has been developed for the metal injection process and chip packaging.

In this paper, on the basis of improvements in the femtosecond laser wet etch technology and the metal microsolidification process, a miniaturized Rogowski coil current transducer is achieved. The most important aspect of this development is that the test results show that the miniaturized Rogowski coil current transducer reveals ultrafast response speeds and good capability for detection of high-frequency electrical signals. This work addresses the two main problems with the realization of feasible 3D microcoils: (1) injection and solidification of high-melting-point metallic materials in the complex 3D channel, and (2) development of a robust but simple packaging method to connect the 3D microcoils to the external electric devices.

2. Experimental

A schematic illustration of the microcoil manufacturing process is shown in figure 1. The process includes three steps: formation of the 3D microchannels, oxygen plasma treatment of the PDMS substrate and the fused silica chip, and the injection of the liquid alloy into channels in the fused silica. First, fabrication of the required 3D helical microchannels requires a femtosecond laser beam, which is created by a regeneratively amplified Ti:sapphire laser system (Coherent Libra-up-he), focused inside the fused silica substrate by a microscope objective lens (Nikon, N.A. of 0.9). The channel is written by translating the 3D stage on which the substrate is fixed on along the pattern path at a speed of 10 μm s⁻¹, as shown in figure 1(a). The laser power is 5 mW. Second, the coil sample was then immersed in an ultrasound assisted 10% HF solution for about one hour and the hollow spiral channel with dimension of 40 μm is obtained, as shown in figure 1(b). Third, a commercial alloy is subsequently injected into the manufactured helical microchannel to produce the conductive microcoils. The alloy used in this case mainly contains metal stannum, bismuth, and lead (melting point = 92.6 °C).

To create the connector required for the injection process, a fused silica sample is placed on a previously prepared polydimethylsiloxane film, as shown in figure 1(c). Because the alloy has a high melting point, the injection process was conducted at a temperature of about 190 °C in a heating chamber. However, the reversibly-bonded PDMS substrate and the silica chip will be separated because of the considerable difference in their coefficients of thermal expansion (CTE) (CTE of silica = 5.5 × 10⁻⁶/°C, CTE of PDMS = 3.0 × 10⁻⁴/°C). Therefore, we optimally treated the PDMS substrate and the silica chip with the oxygen plasma for 80’s and then bonded them together under room temperature conditions.

Two syringe needles are then inserted into the PDMS film at the channel entrance to connect the completed coils. The entire channel will be penetrated as it is integrated. When the temperature reaches the alloy melting point, the alloy is rapidly liquefied. During this injection process, two syringes...
were used to inject the liquid metal into the fabricated micro-channel. The liquid alloy is then injected into one side of the coil using a syringe pump at a low speed of 0.1 ml h$^{-1}$ to generate a high pressure. Simultaneously, a suction pump in the other entrance provides a negative pressure to suck the liquid alloy into the microchannel. When the sample cools down to room temperature, the gallium metal fully fills the coil channels, as shown in figure 1(d). The conductance of the micro-heater is ensured by an optical microscope and an ohmmeter.

Additionally, a wire has been threaded through the central holes in the silica chip and the PDMS substrate under microscope observation.

3. Results and discussion

The fabricated Rogowski coil current transducer is shown in figure 2. The coil line pattern consists of toroidal form windings, encircling the current path, as shown in Figure 2(a). Figure 2(b) shows the microchannel of the coil after HF etching. The coil wire diameter is about 42 $\mu$m; the radius of the toroid and that of the coil loop are 400 $\mu$m and 100 $\mu$m, respectively; the overall size of the Rogowski coil is less than 1 mm in diameter, as shown in figures 2(c) and (d). A wire (diameter ~70 $\mu$m) was then threaded through the central holes in both the silica chip and the PDMS substrate to supply the input electric signals. The uniform microchannels with such complex geometry pattern of Rogowski coil demonstrate the advancement of improved femtosecond laser wet etch technology. The normal laser-assisted chemical etching process usually results in conical-shaped microchannels as the two entrances of channels suffer a longer etching time. As reported in our previous studies [14, 15], the improvements of introducing extra access ports and a secondary power compensation in the process reinvigorate this method significantly. The extra access ports connect the sample surface and the internal microchannels, and import more HF acid directly into the central part, which improves the aspect-ratio and diameter uniformity of the microchannel and reduce the etching time. The power compensation process further improves the uniformity of the channels.

The voltage produced by the Rogowski coil was transported via the electrodes. A schematic illustration of the testing process is shown in figure 3.

The input electrical signal was supplied by a function generator (Tektronix, AFG3102). The input and output voltages were recorded using a digital storage oscilloscope (Agilent Technologies, DSO5012A).
The voltage output by the Rogowski coil is a function of the rate of change of the current threading the coil. 

\[ u(t) = A s \mu_A I(t) \]  

Here, \( A \) is the winding cross-section, \( s \) is the number of turns per unit length, and \( I(t) \) represents the rate of change of the input current. From the test results shown in figure 4, we find that the Rogowski coil displays an ultrafast response time (<1 ns) and good capability for detection of high-frequency electric signals. Based on the theoretical study of Pellinen et al [17], the transit time of the coil is largely decided by its geometry, in that a miniaturized coil will provide a much faster response time of several tens or hundreds of picoseconds (ps).

The electrical parameters of the miniaturized current transducer, including the Rogowski coil and the two electrodes, were evaluated as follows: the resistance value was measured to be 2.2 \( \Omega \), and the inductance and distributed capacitance values were calculated to be about 10 nH and about 0.15 pF, respectively, according to the appropriate theoretical formulas [18]. Similarly, we analyzed the Rogowski coil’s operating bandwidth using Ray et al’s theoretical formulas [7]. The lower frequency limit \( f_L \) is approximately 1 MHz, given that the device’s connection resistance \( (R_0) \) to external facilities is 0.1 \( \Omega \). The working capability of the coil in the high-frequency waveband is determined by the upper-frequency limit \( f_H \) [19]:

\[ f_H = \frac{1}{4 \sqrt{LC}} \]  

(2)

\[ f_L \approx \frac{R_0}{2\pi L} \left(1 + \frac{R}{R_0}\right) \]  

(3)

Here, \( L \) is the coil inductance and \( C \) is the capacitance. Because of the inherent time delays in large coils, \( f_H \) is usually no more than 1 MHz for normal-sized Rogowski coils. Here, the upper-frequency limit \( f_H \) of the miniaturized current transducer was calculated to be about 13 GHz. With a miniaturized coil and more compact packaging, \( f_H \) can be improved to more than hundreds of gigahertz. Therefore, to realize a super-high-frequency Rogowski coil, it is necessary to use a miniaturized coil with low inductance and capacitance [18].

About ten devices were manufactured to test their performance. With the exception of two or three unsuccessful devices, the majority of the devices gave a very good performance. The process of fabricating is controlled by a computer, so the consistency of the geometrical parameters of the devices is guaranteed. For example, the diameter of the coil designed is 40 \( \mu \)m. The mean diameter of the fabricated samples is 42.5 \( \mu \)m; the deviation of the diameter is 4.7%.

In addition to providing the potential capability for working in the super-high frequency waveband and the potential for integration with functional microsystems, Rogowski coils fabricated by FLWE and microsolidification technology will have the additional advantage of high precision. Shafiq et al found that the analytic equations of the Rogowski coil are less effective because of the construction problems caused by traditional fabrication methods: e.g. distribution of turns along the coil is not even, the return path is not in the center of windings and the cross-section is not circling ideally and it turns to an ellipse due to bending. For high-frequency applications, exact parameter determination is important, since the bandwidth and choosing the damping resistor in the terminal is related to these parameters values [20]. It has also been shown that the fabricated metal Rogowski coil is embedded within the rigid block of fused silica, where effective device protection will be guaranteed.

It is worth mentioning that the femtosecond laser fabrication of porous and netlike surface structures can be extended to other metals. For example, we have obtained similar structures on titanium, titanium alloy (Ti6Al4V) and aluminum. Furthermore, to reduce the processing time, the structures were prepared in regions with dimensions of 100 \( \times \) 100 \( \mu \)m². However, it is quite simple for us to fabricate the structures in much larger areas.
4. Conclusions

In conclusion, we have reported a miniaturized Rogowski coil current transducer that was fabricated using an improved femtosecond-laser-based microsolidification technology. The test results show that the miniaturized Rogowski coil current transducer displays ultrafast response speeds and has a good capability for high-frequency electric signal detection. The operating bandwidth can be more than 10 GHz, according to the analysis results. The miniaturized Rogowski coil can easily be integrated into functional microsystems, and can be applied to precision measurements.

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