Ferrofluid-based Stretchable Magnetic Core Inductors

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Abstract. Magnetic materials are commonly used in inductor and transformer cores to increase inductance density. The emerging field of stretchable electronics poses a new challenge since typical magnetic cores are bulky, rigid and often brittle. This paper presents, for the first time, stretchable inductors incorporating ferrofluid as a liquid magnetic core. Ferrofluids, suspensions of nanoscale magnetic particles in a carrier liquid, provide enhanced magnetic permeability without changing the mechanical properties of the surrounding elastomer. The inductor tested in this work consisted of a liquid metal solenoid wrapped around a ferrofluid core in separate channels. The low frequency inductance was found to increase from 255 nH before fill to 390 nH after fill with ferrofluid, an increase of 52%. The inductor was also shown to survive uniaxial strains of up to 100%.

1. Introduction
The development of soft, stretchy electronics in recent years has opened up a range of new applications such as biomedical monitoring, soft robotics and wearable computing [1]. A major challenge has been the creation of high performance stretchable inductors for wireless power and data transmission. The rigid magnetic materials common in inductors design are not easily translated to the stretchable domain. Previous stretchable inductors have instead been built in non-magnetic elastomers such as silicone or polyurethane, resulting in poor inductance density. In previous work, the first stretchable magnetic core inductor based on soft silicone loaded with magnetic particles was demonstrated [2]. The resulting magnetic composites had permeabilities as high as 2.9, while retaining the ability to stretch up to 100% without permanent damage. One disadvantage of this approach, however, is that the resulting composite has different mechanical properties from the original elastomer. The embedded particulate serves to crosslink neighbouring polymer chains, similar to vulcanized rubber, resulting in increased elastic modulus. Although the composites demonstrated stretchability, the greater mechanical stiffness could complicate interfacing with softer surfaces such as human skin.

In this work, the fabrication and testing of a magnetic core stretchable inductor using a ferrofluid as a core material is presented. Ferrofluids are stable suspensions of magnetic particles, typically with particle size on the order of 10 nm to prevent settling due to gravity [3]. Since the core is liquid, the mechanical behaviour of the surrounding elastomer is unchanged unlike in the case of the particle loaded composite. The stretchable inductor traces are made using a room temperature liquid metal in fluidic channels [4], allowing millimeter-scale cross sections for low resistance while

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retaining stretchability. The resulting magnetic core inductor was found to have 52% higher inductance after ferrofluid fill, and retained functionality up to 100% uniaxial strain.

2. Fabrication

A fabrication process for creating a solenoid inductor based on molding silicone using a two-part 3D printed mold was developed in [5]. A modified version (Fig. 1) was used to create three layers of fluidic channels (top and bottom layers filled with liquid metal to form the solenoid, and a middle layer filled with ferrofluid). The process begins by filling a three-part mold with precursors of a soft silicone (Ecoflex 00-30, Smooth-on) (Fig. 1 (a)). The molds used in the process are shown in Fig. 2. As in the original two layer process, the top and bottom molds are used to define the solenoid inductor, while a pedestal defined in the bottom mold sets the placement of a 3D printed bar that defines the ferrofluid core. After the silicone is cured completely at 85°C on a hotplate, it is removed from the mold (Fig. 1 (b)). Since the molds are rarely perfect in contact, a thin layer of silicone remains in the via holes, requiring coring to form holes using a syringe tip.

![Fabrication process: (a) pour silicone elastomer into mold, (b) cure completely and remove, (c) pull out bar defining ferrofluid core (d) seal top and bottom to partially cured silicone and (e) fill with liquid metal and ferrofluid](image)

At this stage, the bar defining the void for the ferrofluid remains embedded within the silicone. Since silicone does not adhere well to the 3D printed polycarbonate, it is then possible to slide the embedded piece out of the silicone (Fig. 1 (c)), a technique previously demonstrated using low friction fibers to define channels in [6]. The bottom channels are then sealed by laying the molded piece onto a pool of Ecoflex 00-30 that has been partially cured for one hour and fifteen minutes at room temperature to minimize the possibility of flowing into the channels (Fig. 1 (d)), a process that is then repeated to seal the top channels as well. Inlet and outlet holes are then cored out using a narrow gauge syringe tip, and the two channels are filled with galinstan and ferrofluid (Ferrotec EFH-1) for the electrical trace and core respectively. The holes are then sealed using drops of silicone. The final fabricated inductor after fill is shown in Fig. 3. Electrical connection for testing is made using copper wires at the inlet and outlet ports, which are in mechanically isolated regions (the tabs extending off the sides of the main inductor test piece) to minimize effects of stretching on the contacts.
3. Testing

The solenoid inductor fabricated in this work consisted of 8.5 turns, with traces one millimeter in width and thickness. The effective core length was defined to be 21 mm, with total core width and thickness of 6 mm and 7 mm respectively. Due to the need for a layer of silicone to isolate the ferrofluid from the channels containing the liquid metal, the ferrofluid portion of the core is only 4 mm by 5 mm, filling 48% of the total core area. The inductor frequency response (Fig. 4) was measured with an HP 4294A impedance analyser before and after filling with the ferrofluid EFH-1 (Ferrotec, \(\mu_r \approx 3.6\)). The low frequency inductance was found to be 255 nH before fill, and rose to 390 nH after being filled with ferrofluid, an increase of 52%.
Both the ferrofluid-filled inductor and a second stretchable inductor with a solid silicone core were also characterized mechanically using a custom uniaxial strain testing setup, consisting of 3D printed clamps designed to fit on a standard bench vise. The test piece is clamped on each end, with a raised zigzag pattern in the clamp designed to bite into the silicone and minimize sliding. The bench vise is then used to adjust the clamp position along the threaded rod, while the position is measured using calipers to determine the applied strain. Fig. 5 shows the ferrofluid inductor during testing up to 100% uniaxial strain.

The inductance of a coil of wire is dependent on the geometry, with both the self inductance of individual traces as well as the coupling to neighboring traces varying with strain. A model for the effects of stretching on a solenoid was previously developed in [5], finding that, for applied strain parallel to the core, the inductance declines rapidly with strain as the core length increases and the core cross sectional area decreases. This behaviour is evident in the silicone-cored inductor as shown in Fig. 6. For the ferrofluid inductor, the drop in inductance was even faster, with the inductance asymptotically converging to the non-magnetic behavior for higher strains. This is likely due to the drop in core cross section, as well as to the overall flattening of the solenoid for large strains. A similar drop in effective permeability was also found for the magnetic-loaded polymer based stretchable inductors in [2].
4. Conclusion

A magnetic core stretchable inductor was demonstrated using ferrofluid within a liquid metal solenoid. The ferrofluid was found to significantly enhance the inductance density of the inductor, increasing the total inductance by 52% after ferrofluid fill. The inductor was tested up to 100% uniaxial strain without damage, although the effect of the ferrofluid dropped rapidly with higher mechanical strains. This makes the device particularly valuable for strain sensing, one of the original applications for liquid metal inductors [4], since the ferrofluid results in a larger change in inductance with strain. Since most biomedical applications require use only up to about 30% strain, the stretchability of skin over much of the human body, this is also a useful improvement for creating an inductor for wireless power or data transmission in a stretchable system.

5. References

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