Wirelessly powered micro-tracer enabled by miniaturized antenna and microfluidic channel

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Abstract. A miniaturized antenna, 380μm by 380μm in size, was fabricated and integrated with a commercialized passive RFID chip to form a micro-tracer, whose size was 2mm by 1mm in total. The micro-tracer was wirelessly powered and interrogated by a single layer spiral reader antenna through near field coupling. To maximize the working distance, the resonant frequency of micro-tracer and reader antenna were matched at 840MHz. Due to the ultra small size of the tracer antenna, power transfer efficiency decreased dramatically as the distance between tracer antenna and reader antenna increased, thus the working distance of the micro-tracer was limited within 1mm. To achieve massive operation of the micro-tracer, a microfluidic platform was fabricated with in channel focusing and separation. Acrylic sheets were laser cut to define the channel and cover structure, then bonded together layer by layer with a glass substrate, on which reader antenna was integrated. Pump oil was used as the fluidic media carrying the micro-tracer flowing inside the microfluidic channel. The wireless power transfer and real-time communication was demonstrated with the micro-tracer flowing above the reader antenna, as the ID of the micro-tracer was retrieved and displayed on a computer screen.

1. Introduction
Thanks to CMOS and microelectromechanical systems (MEMS) technologies, integrated circuit (IC) and physical sensor’s feature size has been successfully reduced to micrometre (μm) scale [1, 2]. This enabled the possibility of integrated microsensors. With miniaturized size, microsensors can play important roles in various areas, such as health and environmental monitoring, homeland security, and natural resource exploration, among others. However, for a functional sensor, especially in micrometer range, wireless communication and battery charging are always required, thus an integrated antenna is needed. Nevertheless, the radiation efficiency of small antennas follows the Chu-Harrington limit [3], setting a minimum size for the far-field antenna design for a given frequency. Therefore, near field wireless communication stands out as a viable option.

In our study case, to achieve successful size miniaturization, near field with higher power density and less demand of antenna dimension is utilized. Due to the short propagation distance of near field, sensors, that are designed to operate at distant locations, are usually dispatched to the target environment and then collected back to retrieve stored information [4]. In this paper, a 380μm by 380μm double layer antenna was designed, fabricated and integrated with a commercialized RFID chip [5] to form a micro-tracer 1mm by 2mm in size. The micro-tracer can work alone or be integrated with sensors and a battery to form a microsensor. A spiral reader antenna was designed and fabricated

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to work with the micro-tracer. Wireless communication and power transfer was successfully realized at 1mm distance. A microfluidic channel platform with focusing and separation functions was designed to manipulate multiple miniature tracers.

2. System design and fabrication

2.1. Antenna design
A commercialized RFID chip was chosen to form the micro-tracer with an impedance of 18.6-j171.2 at the frequency of 915MHz. Due to the negative imaginary portion, the RFID could be treated as a capacitance in series with a resistance. A double layer spiral antenna was designed as an inductance to match the impedance of the RFID chip to maximize the power transfer efficiency. Antennas with different side lengths were designed and simulated in CST Microwave Studio to find the optimized antenna dimension. The simulation results are shown in table 1. Identical line width (10μm) and number of turns (4) are applied in the simulation. From the simulation results, it can be seen that the impedance match is realized at a side length between 360μm and 380μm.

Table 1. The simulation result of micro-tracer antennas with different side length.

| Type  | Side length (μm) | Imaginary portion | Inductance (nH) |
|-------|-----------------|-------------------|-----------------|
| Type1 | 340.0           | 140.8             | 24.5            |
| Type2 | 360.0           | 162.0             | 28.2            |
| Type3 | 380.0           | 181.8             | 31.6            |
| Type4 | 400.0           | 203.1             | 35.3            |

The reader antenna was designed as a single layer spiral antenna with a coupling loop as shown in figure 1. The RF signal fed into the coupling loop excites the inner spiral antenna at the resonance frequency, at which maximum magnetic field is generated. The resonance frequencies of the antennas can be accurately designed by varying the spiral coil geometry (e.g., size, number of turns, track and gap widths, etc.), and changing the coupling ratio between the coupling loop and the spiral. This is clearly demonstrated in figure 2, in which the reflection coefficient (S11) were plotted for various antennas with resonant dips.

2.2. Antenna fabrication and chip integration
The fabrication process of the antennas is illustrated in figure 3. The reader and tracer antenna were fabricated on a Pyrex glass substrate with 500μm thickness. A thin layer of copper was evaporated as the seed layer on top of the substrate. Then, 5μm thick photoresist was spun and patterned to define the structure of the first layer of the antenna, after which electroplating was applied to grow the first layer of the spiral to 5μm thickness. The wafer was soaked in acetone to remove the photoresist.
Subsequently, the seed layer was removed by wet etching. At this point, in the case of the reader antenna, the structure was complete while in the case of the micro-tracer antenna, another spiral structure was required. SU8, as the separation and supporting layer, was photo-defined to form the vias, which were filled by electroplating to connect the first and second layer. Following the same flow as the first layer fabrication, the second layer of the antenna was fabricated as shown in steps 8 through 12 in figure 3. Finally, a thin layer of silicon nitride was sputtered as an insulation and protection layer. The SEM picture of a fabricated tracer antenna is shown in figure 4. Figure 4 (a) shows that the two layers were connected by a via in the middle, while the pad on the left was connected to the bottom layer. The spiral structure can be seen clearly in figure 4 (b). After antenna fabrication, the antenna and RFID chip was bonded together with silver epoxy to form a micro-tracer.

3. Microfluidic channel design and fabrication

3.1. Microfluidic channel design

A microfluidic channel with cross section of 2mm in width and 1.2mm in height was designed to manipulate multiple micro-tracers. Pump oil was chosen as the fluidic media to transport the sensors flowing inside the channel. Considering large numbers of micro-tracers may arrive at the microfluidic channel simultaneously, in order to avoid clogging, a focusing structure was designed as shown in figure 5 (a). When multiple sensors arrive at the funnel structure, the two side inputs begin pumping at the same time with a high velocity in order to create a focusing effect for the main stream. Thus, the micro-tracers are lined up such that only a single micro-tracer passes the main channel at a time.

Figure 3. Fabrication process of the micro-tracer antenna.

Figure 4. SEM picture of micro-tracer antenna.

Figure 5. Microfluidic channel design. (a) Focusing structure to line up micro-tracers. (b) and (c) Separation structure to prevent reading failure due to collision.
If two micro-tracers are so close that they reach the reading range of the reader antenna simultaneously, data collision may cause reading failure. A separation unit was fabricated to guarantee enough time delay between two deliveries as shown in figure 5 (b) and (c). When one of the micro-tracers reaches side channel 1, the main channel stops pumping while side channel 1 begins to pump. Thus, the newly arrived sensor is forced to the second sidewall with others keeping their position. Next, the side channel 1 stops pumping, while side channel 2 starts to pump and only a single micro-tracer passes the microfluidic channel. In this fashion, by controlling the time delay between two operation circles, an adequate interval delivery time can be guaranteed.

3.2. Microfluidic channel fabrication
The microfluidic channels were composed of three layers: the first layer was a glass substrate, on which reader antennas were fabricated, the second layer was the structure of the channel, and the third layer was the channel cover. The second and third layers were fabricated by laser cutting an acrylic sheet. As the thickness of the acrylic sheet was 0.5mm, two layers were stacked together to form the channel layer. The three layers were bonded together with epoxy adhesive. A syringe was connected to the microfluidic channel through a soft pipe, which was inserted into the connection ports; the flow speed inside the channel was controlled by a syringe pump. The reader antennas were wire bonded to SMA connectors, which were connected to the reader circuit through co-axial cable. The fabrication process is illustrated in figure 6 (a) and the fabricated microfluidic channel is shown in figure 6 (b).

![Figure 6. (a) Microfluidic channel fabrication process. (b) Picture of the microfluidic channel.](image)

4. Experiment and result
After micro-tracer integration and microfluidic channel fabrication, we performed the in-channel real-time communication experiment. The experimental setup is shown in figure 7 (a). The reader antenna
was embedded below the microfluidic channel, and connected to the reader circuit through a co-axial cable, which was powered and controlled by a computer using a USB cable. A micro-tracer was placed inside the microfluidic channel and pump oil was employed as the carrying media to transport the micro-tracer within the microfluidic channel. A syringe pump was connected to one end of the microfluidic channel to control the flow speed, while the other end of the channel was connected to an oil reservoir. As the oil flowed, the micro-tracer travelled across the reader antenna. When the communication link was complete, the ID information of the RFID was retrieved and displayed on the computer screen as shown in figure 7 (b).

5. Conclusion
We developed a prototype of integrated microfluidic channels to interrogate micro-tracers using near field RF communication technique. A miniaturized antenna was designed and optimized to match its impedance with a RFID IC chip within a limited chip area (< 400µm×400µm). After the integration of the antenna and RFID IC, wireless communication was demonstrated in the microfluidic channel. Beyond the specific application developed in this work, the micro-tracer may also be employed as a communication unit for a variety of MEMS sensors.

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