

# Tri-Axis Receiver for Wireless Micro-Power Transmission

Nan-Chyuan Tsai, Sheng-Liang Hsu

**Abstract**—An innovative tri-axes micro-power receiver is proposed. The tri-axes micro-power receiver consists of two sets 3-D micro-solenoids and one set planar micro-coils in which iron core is embedded. The three sets of micro-coils are designed to be orthogonal to each other. Therefore, no matter which direction the flux is present along, the magnetic energy can be harvested and transformed into electric power. Not only dead space of receiving power is mostly reduced, but also transformation efficiency of electromagnetic energy to electric power can be efficiently raised. By employing commercial software, *Ansoft Maxwell*, the preliminary simulation results verify that the proposed micro-power receiver can efficiently pick up the energy transmitted by magnetic power source.

As to the fabrication process, the isotropic etching technique is employed to micro-machine the inverse-trapezoid fillister so that the copper wire can be successfully electroplated. The adhesion between micro-coils and fillister is much enhanced.

**Keywords**—Wireless Power Transmission, Magnetic Flux, Tri-axes Micro-power Receiver

## I. INTRODUCTION

DUE to the progress of micro-machining technique, the meso-scale devices and micro-scale systems, such as wireless sensor networks, capsule endoscope, micro drug delivery system, RFID and tire pressure monitoring system, are gradually mature and commercialized ([1]-[3]). However, to work for a long period of time, those devices still need continuously-supplied power. No matter the power is transmitted by wire or supplied by battery, the size of the device has to greatly increase. Moreover, owing to special working environment, some kinds of devices, such as micro-endoscope and micro-drug delivery, cannot carry sized batteries. Wireless power transmission and MEMS energy harvester are two potential technologies to solve this problem.

The principle of MEMS energy harvester is to harvest energy from nature and then transform into electrical power. Different from MEMS energy harvester, the energy source of wireless power transmission can be actively supplied via transmitters. Although the additional cost due to actively supply power is necessary, the received power by the device is considerably stable.

In the literature, a few research reports, e.g., design of receiver [5], micro-robot [6], capsule endoscope [7], miniature ignition system [8], sensor modules [9], implantable system [10], are presented. In general, for wireless power transmission, the central axes of transmitter and receiver are

usually assumed to be perfectly aligned. However, in practice, the misalignment angle of receiver with respect to the central axis of transmitter is always present due to inaccuracy of assembly or imperfect fabrication. In order to solve this problem, a platform design of wireless power transmission is proposed [6]. The platform allows that micro-robot to move under the conditions of lateral alignment and angular alignment between transmitter and receiver.

In our work, an innovative tri-axes micro-power receiver, consisting of two sets of micro-solenoids and one set of micro-planar coils, is proposed. The two sets of micro-solenoids and one set of micro-coils are designed orthogonal to each other. Most importantly, for each set of micro-coil/micro-solenoid, an iron core is embedded so that the energy transformation efficiency can be much improved.

## II. MATHEMATICAL DESCRIPT FOR WIRELESS POWER TRANSMISSION

It is well known that if a straight wire is energized by electric current, a magnetic field is induced simultaneously. By Ampere's law, the relation between the applied current and magnetic flux density can be expressed as follows:

$$\oint B \cdot d\ell = \mu_0 I \quad (1)$$

where  $B$ ,  $\mu_0$  and  $I$  represent the induced magnetic flux density (Tesla), permeability of media and the applied current respectively. The magnetic field density at Point P away from the conductor can be evaluated as follows [12]:

$$B = \frac{\mu_0 \cdot I \cdot L}{2\pi r \sqrt{L^2 + r^2}} \quad (2)$$

where  $r$  represents the distance between conduct or point P, shown in Fig. 1. Similarly, for application to wireless power transmission, the conductor is like a solenoid. Once current is applied on the conductor, the magnetic field is generated simultaneously. The magnetic field intensity away from the central line of conductor can be derived by Biot-Savart law as follows:

$$H = \frac{I \cdot R^2}{2\sqrt{(R^2 + z^2)^3}} \quad (3)$$

where  $H$ ,  $R$  and  $z$  represent the magnetic field intensity (H/m), radius of the solenoid and distance between the interested point and the solenoid. It is noted that the relations,  $B = \phi / A$  and  $B = \mu H$ , hold in this paper. The magnetic

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flux  $\phi$  can be represented as follows:

$$\phi = \mu \cdot A \cdot \frac{I \cdot R^2}{2\sqrt{(R^2 + z^2)^3}} \quad (4)$$

where  $\phi$ ,  $\mu$  and  $A$  represent magnetic flux, permeability and cross-sectional area. From the viewpoint of power transmission, Eqs.(1~4) are to describe the induced magnetic field by the "transmitter".

On the other hand, the induced voltage at receiver can be obtained by Faraday law. The equation of induced voltage at receiver can be written as follows:

$$\varepsilon = -N \frac{d\phi}{dt} \quad (5)$$

where  $\varepsilon$  and  $N$  represent the induced voltage and numbers of winding at receiver.

### III. DESIGN OF TRI-AXIS MICRO-POWER RECEIVER

#### A. Tri-axes Micro-power Receiver

The schematic diagram of tri-axis micro-power receiver is shown in Fig. 3. The tri-axis micro-power receiver is composed of 3 sets micro-solenoids, i.e., Sets A, B and C. Micro-solenoid set A/B consists of two individual micro-solenoids parallel to each other. The same pair of micro-solenoid is wound by the same copper wire. That is, the magnetic flux in X-direction and Y-direction are to be harvested by these two pairs of micro-solenoid. The two sets of micro-solenoids are perpendicular to each other like a square. On the other hand, the magnetic flux in the Z-direction is to be harvested by the set of micro-solenoid C placed at the center of the receiver. Set C consists of 4 identical individual micro-solenoids (C1, C2, C3 and C4) in which the embedded iron cores are along the direction of Z-axis. In order words, all components of magnetic flux around the receiver can be harvested, as shown in Fig. 4 and Fig. 5.

#### B. Verification of Tri-axes Micro-power Receiver Design

In order to verify the efficacy of the tri-exes micro-power receiver, the obtained electric power is evaluated by computer simulation. The commercial software, Ansoft Maxwell, is employed in our research. In addition to the power harvested to be considered, the design parameters, such as sizes of micro-coils and iron core, are also examined for later fabrication. Assume the distance between transmitter and receiver is 5cm. The design parameters of micro-power receiver and transmitter are listed in Table 1 and Table 2. Firstly, the transmitter is energized by an alternating voltage. The induced voltage at each micro-solenoid set is shown in Fig. 6. The distribution of induced magnetic flux density at receiver is shown as Fig. 7. It is noted that at time instant 0.65msec (see Fig. 7(d)), the induced voltage is the maximum shown in Fig. 6. The corresponding maximum of magnetic flux density shown in Fig. 7(d) is about 1.0 Tesla. The endured magnetic density by iron core is greater than 1.0 Tesla so that the iron core at Fig.

7(d) is not saturated yet as the applied current at transmitter is less than 400 A.

### IV. FABRICATION OF TRI-AXES MICRO-POWER RECEIVER

The fabrication processes of micro-power receiver can be divided into three stages. The fabrication process for bottom layer of micro-solenoids is described at section A. At second stage, the iron core and upper layer of micro-solenoid are fabricated. At final stage, the multi-layer structure of the receiver is constructed. In our work, the micro-coils are fabricated onto inverse-trapezoid fillister so that the contact angle of wire against fillister can be increased. Besides, the conventional design defect, too much void within the plated copper wire, can be prevented.

#### A. Bottom Layer of Micro-solenoid A/B and First Layer of Micro-Solenoid C

The fabrication processes for the bottom coil of micro-solenoid A/B and first layer of micro-solenoid C are shown in Fig. 8.

- (a) A thin film of silicon nitride ( $\text{Si}_3\text{N}_x$ ), with thickness 100nm, is deposited on the wafer by PECVD (Plasma Enhanced Chemical Vapor Deposition). This layer of  $\text{Si}_3\text{N}_x$  is used as the Etching Mask prepared for the KOH non-isotropic etching which will be undertaken later. A thin film of aluminum (Al), with thickness 100nm, is deposited above the  $\text{Si}_3\text{N}_x$  film on the wafer. Al is not etched by ICP (Inductively Coupled Plasma) so that this layer can be used as an Etching Mask for ICP. The photo-resist AZ-4620 is deposited onto the film of Al and then photo exposure process is undertaken so that the etching mask made by Al is patterned and defined. By using ICP, the etching mask made by  $\text{Si}_3\text{N}_x$  is patterned and defined.
- (b) KOH solution is used for non-isotropic etching of silicon. The temperature and time are set as 80 degrees and 160 minutes. The inverse-trapezoid fillister, with depth 120 $\mu\text{m}$ , is constructed.
- (c) The fabrication process of Etching Mask for iron core of micro-solenoid C is as same as (a).
- (d) KOH solution is used for non-isotropic etching of silicon. The temperature and time are set as 80 degrees and 20 minutes. The inverse-trapezoid fillister, with depth 15 $\mu\text{m}$ , is constructed.
- (e) A seed layer of chromium (Cr), with thickness 100nm, is deposited by E-beam evaporator to enhance the coherence efficacy of copper layer which is to be deposited in the follow-up electroplating process in (g).
- (f) The photo-resist KMPR is deposited on the wafer by automatic spin coating system and then photo exposure process is undertaken. The patterned KMPR is used as mold for bottom layer of micro-solenoid A/B and first layer of micro-solenoid C.
- (g) The copper layer is deposited into the mold by

electroplating.

- (h) KMPR stripper and Cr etchant are used to remove KMPR and seed layer (Cr) respectively.

### B. Iron Core and Upper layer of Micro-solenoid A/B

Fabrication processes for iron core of micro-solenoid A/B, upper layer coil of micro-solenoid A/B and via are shown in Fig. 9.

- (i) A layer of photo-resist SU-8 is coated by spin coater and then patterned by photo exposure process. The defined Su-8 photo-resist is used as the insulator to prevent from short circuit of bottom layer coil. A seed layer (Cr) is coated by E-beam evaporator.
- (j) A layer of photo-resist KMPR is coated and then patterned by photo exposure. The defined KMPR is used as the mold for iron core of micro-solenoid coil.
- (k) By electroplating, the iron core is filled into the mold prepared in (j).
- (l) By KMPR stripper and Cr etchant, the photo-resist KMPR and seed layer (Cr) are removed in order.
- (m) A layer of photo-resist SU-8 is coated by spin coater and then patterned by photo exposure. The insulator for bottom layer and upper layer of micro-solenoid coil is developed.
- (n) A seed layer (Cr) is coated by E-beam evaporator. A layer of photo-resist KMPR is coated by spin coater and patterned by photo exposure. The defined KMPR is used as the mold for upper layer coil and via.
- (o) The copper is filled into the mold prepared in (n).
- (p) The KMPR stripper is employed to remove KMPR and then Cr etchant is used to remove seed layer (Cr).

### C. Second Layer to Forth Layer for Micro-solenoid C

Fabrication processes of the second layer to forth layer are shown as Fig. 10.

Finally, the fabricated tri-axis micro-power receiver is shown as Fig. 11.

## VI. CONCLUSION

In our research, an innovative tri-axes micro-power receiver is proposed. This tri-axes micro-power receiver consists of two sets of 3-D micro-solenoids and one set of planar micro-coils in which iron core are embedded. No matter which direction the magnetic flux be present along, the magnetic energy can be harvested and transformed into electric energy. The contact angle and contact surface can be much increased by the proposed fillister design so that the adhesion efficiency between plated coil and the substrate can be effectively improved. The design and expected efficacy of proposed micro-power receiver is verified by computer simulation. Finally, the fabrication process is designed to realize the micro-power receiver.

## ACKNOWLEDGMENT

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## REFERENCES

- [1] <http://www.givenimaging.com/en-us/Patients/Pages/CapsuleEndoscopy.aspx>
- [2] <http://mmadou.eng.uci.edu/Drug%20Delivery.html>
- [3] [http://www.ti.com/ww/tw/prod\\_rfid.html](http://www.ti.com/ww/tw/prod_rfid.html)
- [4] P.-H. Wang, X.-H. Dai, D.-M. Fang, and X.-L. Zhao, "Design, fabrication and performance of a new vibration-based electromagnetic micro power generator," *Microelectronics Journal*, vol. 38, pp 1175– 1180, 2007.
- [5] S.-I. Kim, D. H. Lee, Y. P. Lee, Y. S. Chang, and M.-C. Park, "Low frequency properties of micro power generator using a gold electroplated coil and magnet," *Current Applied Physics*, vol. 8, pp. 138– 141, 2008.
- [6] J. Gao, "Traveling Magnetic Field for Homogeneous Wireless Power Transmission," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, January 2007.
- [7] K. Wang, G. Yan, P. Jiang, and D. Ye, "A Wireless Robotic Endoscope for Gastrointestine," *IEEE Transactions on Robotics*, vol. 24, no. 1, February 2008.
- [8] G. A. A. Rodriguez, C. Rossi, and D. Esteve, "Design, fabrication and operation of a wireless and miniature ignition system," *Sensors and Actuators A*, Vol. 126, pp. 201–210, 2006.
- [9] T. O'Donnell, O. Chevalerais, G. Grant, S. C. O'Mathuna, D. Power, and N. O'Donnovan, "Inductive Powering of Sensor Modules," *IEEE Applied Power Electronics Conference and Exposition*, vol. 3, pp. 2024–2029, 2005.
- [10] A. Salim, A. Baldi, and B. Ziaie, "Inductive Link Modeling and Design Guidelines for Optimum Power Transfer in Implantable Wireless Microsystems," *Proceedings of the 25th Annual International Conference of the IEEE EMBS*, September 17-21, 2003, Cancun, Mexico.
- [11] M. Catrysse, B. Hermans, and R. Puers, "An inductive power system with integrated bi-directional data-transmission," *Sensors and Actuators A*, vol. 115, pp. 221–229, 2004.
- [12] D. K. Cheng, *Field and Wave Electromagnetics*. 2nd ed., U.S.A: Addison-Wiley, pp. 232-238, 1989.

TABLE I  
PARAMETERS OF MAGNETIC FLUX TRANSMITTER

Transmitter	
Inner radius	80mm
Outer radius	100mm
# of winding	200 turns
Applied voltage	400V
Resistance	1 Ω

TABLE II  
PARAMETERS OF TRI-AXIS MICRO-POWER RECEIVER

Receiver	
Total numbers of micro-solenoid coils	98 turns
Total numbers of micro-planar coils	160 turns
Cross-sectional sizes of micro-coils	20μm × 20μm
Gap of coil-to-coil	20μm

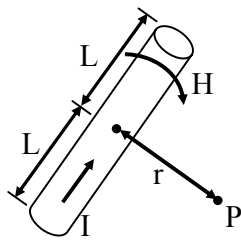


Fig. 1 Magnetic Flux Induced by A Straight Wire

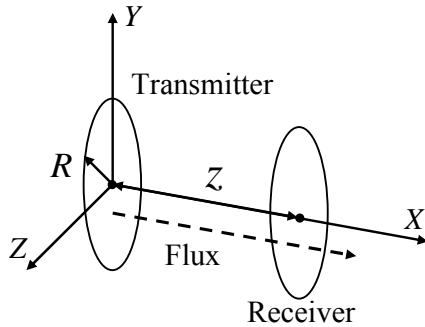


Fig. 2 Transmitter and Receiver for Wireless Power Transmission

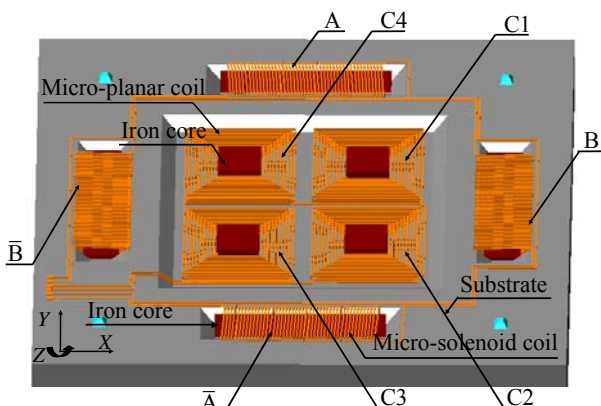


Figure 3 Tri-axis Micro-power Receiver

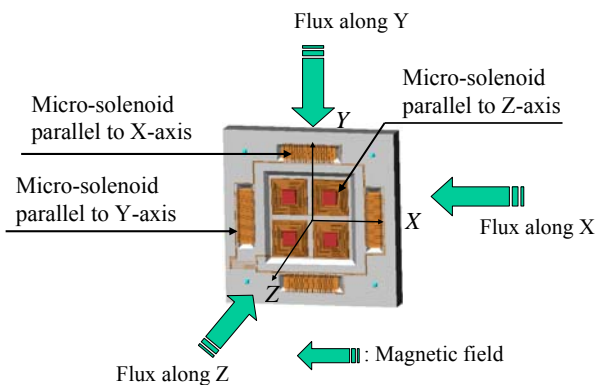
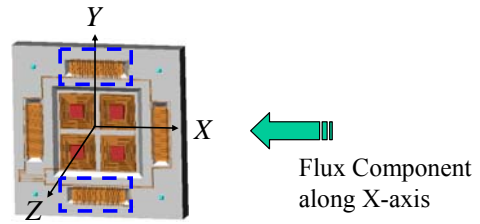
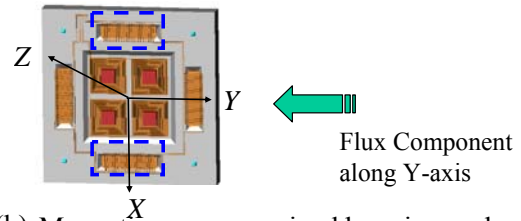


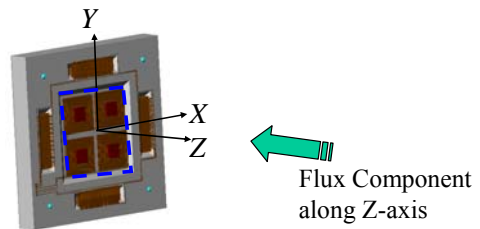
Fig. 4 Magnetic Energy and the Micro-power Receiver



(a). Magnetic energy received by micro-solenoid parallel to X-axis



(b). Magnetic energy received by micro-solenoid parallel to Y-axis



(c). Magnetic energy received by micro-planar parallel to Z-axis

← : Magnetic field

Fig. 5 Magnetic Flux Components Harvested by Micro-power Receiver

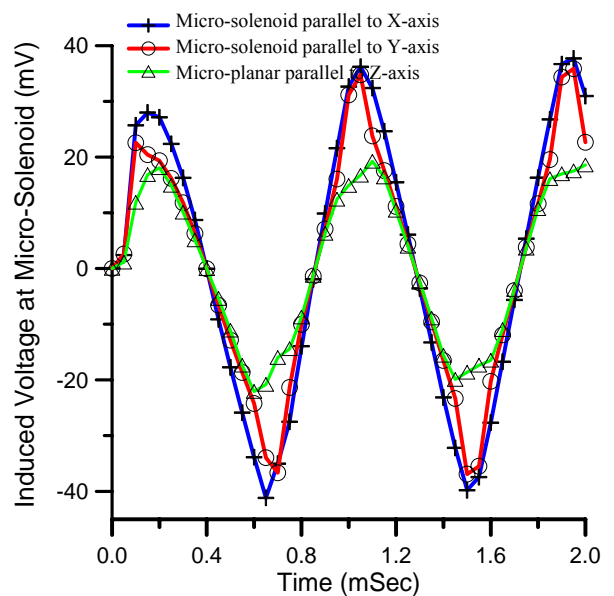


Fig. 6 Induced Voltage at Tri-axis Micro-power Receiver

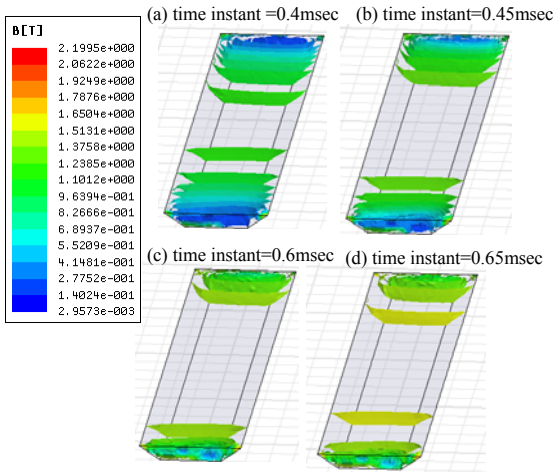


Fig. 7 Magnetic Flux Distribution of Iron Core from 0.4msec to 0.65msec

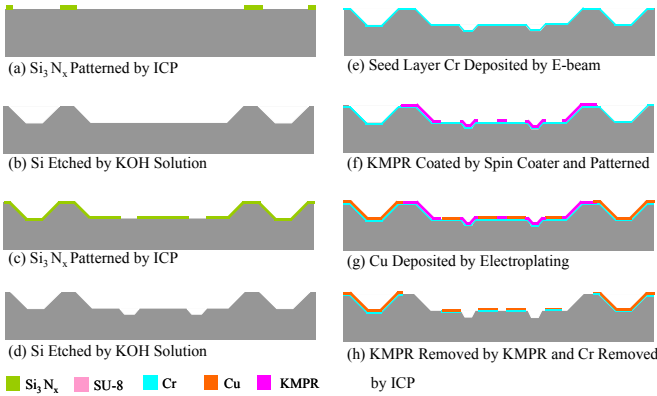


Fig. 8 Fabrication Processes for Bottom Layer Coil of Micro-solenoid (A/B) and First Layer of Micro-planar Coil (C)

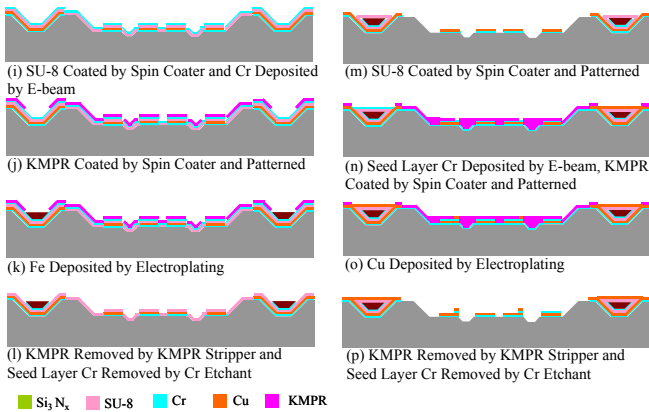


Fig. 9 Fabrication Processes for Iron Core, Insulator of Micro-solenoid and First layer of Micro-planar Coil

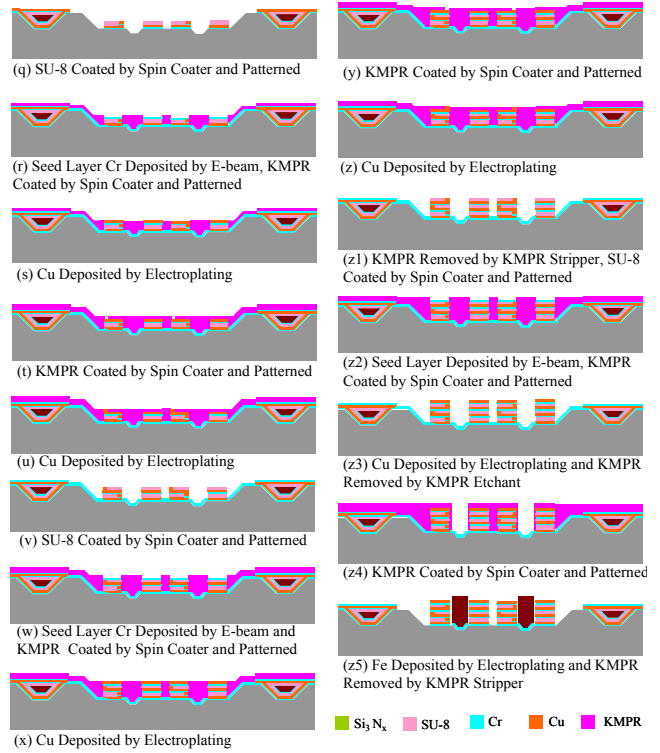


Fig. 10 Fabrication Processes for Second Layer to Forth Layer and Iron Core of Micro-planar Coil

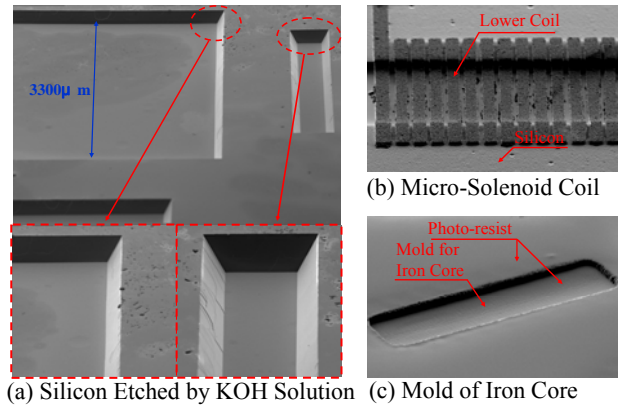


Fig. 11 A Few SEM of Fabricated Tri-axis Micro-power Receiver