SIMULATION AND DESIGN OF MICRO INDUCTOR FOR ELECTROMAGNETIC ENERGY SCAVENGING AT LOW AC FREQUENCY IN WIRELESS SENSOR NETWORK

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Abstract: This paper presents a prototype of wireless sensor node for power management of information and communication technology (ICT) devices at low AC frequency. Electromagnetic simulation and experiments were carried out for discussing the miniaturization of the sensor node. The good fit between the simulation and experimental results on the induction voltage of a commercial meso-scale inductor, suggested that energy scavenging is possible at low AC frequency. However, the measured induction voltage deviated much from the simulated ones with the reducing of inductor size. A careful selection of core material and design is required for realizing micro inductor-based current sensing and power generation by MEMS technology.

Keywords: MEMS, Inductor, Energy scavenging

INTRODUCTION

In the last two decades, there are rapidly increasing interests and effort concentrated into developing energy-efficient technology for less emission of carbon dioxide and other green gases, especially after the adoption of Kyoto Protocol. Information and communication technology (ICT) plays important roles in the development of the energy-efficient technology for many fields including industry, transportation, business and homes. A good example is that radio frequency identification (RFID) technology has assisted supply management in reducing energy consumption by about 5% through allocating vehicles to the most efficient routes [1]. It is believed that the energy consumption of TV and refrigerator for family usage could be reduced by 30% in next three year and 50% in next ten year, respectively, by using ICT devices [1-2].

As a matter of facts, the electricity power consumption of ICT technology itself is increasing enormously with the application of more ICT devices such as servers, network equipments, displays and etc. The electricity consumption of ICT devices is estimated to grow to be 20% of total generated electricity power in the year 2025 [1-2]. In Japan, the electricity consumption of ICT devices would increase by about 4.2 times by the year 2025. The energy consumption of internet data center (IDC) is also rapidly increasing with the increasing amount of data traffic on the internet. It is estimated to grow by two orders of its present value by the year 2025. Therefore, ICT technology needs new energy management technology for reducing the emission of CO2. Wireless sensor network, one of the most promising next generation of ICT applications, are expected to be utilized for this purpose as well as health and security applications. The wireless sensor networks for facility energy controls can generate positive economic impact of 25 billion US dollar or

Fig. 1 Conception of wireless sensor-based power consumption monitoring system for ICT devices.
home. The sensor node is not only for monitoring the electric current flow in appliance cord but also for power generation by the alternating magnetic field surrounded so that it could be cheaper and maintenance-free. Similar work has been reported by Leland and Wright [3-5]. They developed a cantilever-mount piezoelectric bimorph with magnets attached to its free end. The magnets couple to the alternating magnetic field surrounding the power cord, driving the bimorph to generate a voltage that can be used either for current measurement or power generation. This paper presents a new solution based on a clamp-type current sensor and our effort on its miniaturization.

PROTOTYPE AND ELECTROMAGNETIC SIMULATION

We have developed prototypes of a wireless current sensor and graphic user interface (GUI), which could monitor 50 sensor nodes simultaneously. Fig. 2 is photos of the prototype of wireless sensor node.

The sensor node mainly consists of a clamp-type current sensor, thermometer, antenna and other components for the monitoring of the electricity current flow and environment temperature. Using the sensor nodes and GUI, power monitoring of residential and commercial ICT devices could be easily enabled. The clamp-type current sensor has two jaws so that it could detect the current flow through appliance cords. The sensor node has to be set around to only one cable of the appliance cords, as shown in Fig. 2; otherwise, the output signal is very low. The design has the advantage of high sensitivity resulted from stronger alternating magnetic field surrounding one single cable but its practical utilization becomes inconvenient because most appliance cords are difficult to be disassembled into single cables. Such disassemble operation sometimes is even danger. In addition, the prototype sensor is bulky because of the magnetic core and the battery. Therefore, the sensor node is expensive and needs regular maintenance. These shortcomings halt the prototypes from commercial applications. This paper would be focused on the discussion of the miniaturization and self-powering of the sensor node.

The key to the miniaturization of the sensor node is to seeking to develop micro inductor with high performance, which could be utilized as an energy harvester for power generation without the cost of current sensitivity. As the aforementioned, it is not easy to dissemble appliance cords into single cables for loading the sensor node. The appliance plug is therefore interesting because it is easier for the sensor node accessing to strong magnetic field at the appliance plug if a suitable insulation method is used. However, the inductor should be enough small because of limited space near the plug.

Electromagnetic simulation is performed by using Maxwell 3D simulator. Fig. 3 shows a representative schematic of a small inductor on the appliance plug and its meshing information. The magnetic core of the small inductor was 1 mm thick. The core is $16 \times 9$ mm square with a square hole of $6 \times 3$ mm in the
middle. The magnetic core was Mn-Zn ferrite, which is commonly used in radio controlled clock or watch [6]. It has the permeability of about 8000. Although extensive simulation work had been carried out, the effects of fabrication gap on the induction voltage were only introduced here. The gap structure is important for conventional fabrication process. It assists in simplifying the fabrication process and reducing cost. Three representative magnetic cores were investigated, as shown in Fig. 4. Fig. 4 also shows the simulated magnetic fields of the small inductors. The gap structure resulted into obvious flux loss. Figure 5 is simulated induced voltages. The induced voltage was only 0.15 V for the Type C inductor (5 mm long and 200 turns), which is not enough for driving energy scavenging circuit. However, if there were not the gaps, the induced voltage could reach about 0.53 V. The calculated value is based on the assumption that the winding consists of 200 turns, which is corresponding to a pitch of about 25 um. Such a small pitch is difficult to be prepared by conventional machinery without the presence of the gaps, suggesting that microfabrication method should be developed.

EXPERIMENTAL

Home-made inductors were prepared. It had the copper coil of 40 turns with the winding length of 6 mm. The core material was permalloy sheet from Nakano Company, Japan. It was machined into a 12 × 9 mm square with a square hole of 6 × 3 mm in the middle. Fig. 6 (a) shows the prepared inductor. The measurement of induction voltage was measured by using a Tektronix digital oscilloscope. Fig. 6 (b) shows the image of the prepared inductor on the appliance plug. The commercial inductor of the prototype node was also characterized. The commercial inductor has a coil of 800 turns around a ferrite core (U. R. D. co., Ltd, CTL-6-S32-8F-CL).

RESULTS AND DISCUSSION

Fig. 7 is measured induction voltage of the commercial inductor. The simulated results were also plotted. There was a good fit between the measured and simulated values. The simulation also showed that higher induction voltage could be achieved if there were not gaps. It indicated that energy scavenging is possible by using an inductor from the alternating magnetic fields resulted from low AC frequency current flow in the appliance cords.

Fig. 8 is measured voltage of the home-made inductor. The measured value was much lower than the simulated values shown in Fig. 5. The latter was about ~ 285 μV/turn/A while the measured value was only about ~ 18 μV/turn/A. Fig. 9 shows measured waveform of the induction voltage by using the home-made one. It indicated that the saturation of magnetic flux had occurred. This is supported by the simulation results of Fig. 7. The difference between the induction voltage of the core with and without gap tends to small with decreasing AC current. We thought that the phenomenon was mainly related to that a high-permeability core was used. High-permeability core is

Fig. 4 Magnetic field magnitude of coil with different gap structure. Type A is gap-less. Type B is of one gap. Type C is of two gap. The gap is shown in dashed line.

Fig. 5 Simulated induced voltage of micro inductor with different gap structure. Winding is 5 mm long and 200 turns.

Fig. 6 Photo of the home-made inductor and measurement set-up of induction voltage.
subject to flux loss. It was also supported by the fact that the measured induction voltage of the home-made inductor was not improved by using a bigger core. Therefore, the low induction voltage might mainly result from the poor fabrication quality of the coil. Higher voltage output could be expected through improving the fabrication of small inductor. In particularly, with the size reducing of the inductor, a careful design and precise fabrication are necessary.

CONCLUSIONS

This research showed that the energy scavenging was possible with a high-performance micro inductor. The design of magnetic core was important as well as the fabrication of coil. The simulation indicated that microfabrication process is necessary for achieving large number of turns in a limited volume in order to develop a micro inductor for realizing either current sensing or power generation.

REFERENCES