LETTER

Receiver Coil Built Into Belt for Heat Dissipation of Watch-type Smart Devices

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Abstract This letter proposes a novel method to promote the heat dissipation of watch-type smart devices by using receiver coils for wireless charging. It is achieved by embedding a spiral coil inside the belt. The heat dissipation effects of the proposed method on temperatures at key hot spots are clarified. The power transfer efficiency is also clarified. In watch-type smart devices, the most critical part for temperature is the underside surface of the belt, since this is the part that touches the skin for a long time. The analysis results show that the proposed method can reduce the increase in ambient temperature at the belt's underside surface by 59.7% and that its power transfer efficiency is more than 90%.

key words: wearables, smart watches, thermal design, thermal analysis, wireless power transfer.

Classification: Devices, circuits and hardware for IoT and biomedical applications

1. Introduction

With the advances in smart device technology, wearables have become increasingly popular over the past few years. The overall wearables market is segmented into smartwatches, earwear, eyewear, and others. Among these, the global smartwatch market is expected to grow at the CAGR of 18.32% from 2020 to 2026 [1]. Smartwatches are used for wellness, medical, personal assistance, sports, human activity recognition, and other applications [2, 3, 4, 5, 6]. To achieve their purposes, many technologies such as wireless communications and monitoring are being incorporated. Wireless technologies include GPS, Bluetooth, BLE, and Wi-Fi and are typically used for data transmission, notification of calls and mail, and information display. Monitoring is used to collect data for healthcare apps, including heart rate, blood oxygen, blood pressure, sleep patterns, body temperature, number of steps walked, distance travelled, and calories. These apps have been used for discovering diseases [7, 8] and monitoring health conditions [9, 10,

11].

Wireless charging has been implemented in electrical/electronic equipment apps such as electric toothbrushes, electric shavers, and cordless telephones since the 1990s [12]. More recently, wireless charging has been applied to state-of-the-art smartphones and wearables (e.g., smartwatches). The near-field wireless power transfer (WPT) systems feature either inductive or capacitive coupling. Inductive coupling uses a traditional electromagnetic induction method or a magnetic resonant coupling method [13, 14]. The latter can transfer at longer distances than the former. The traditional electromagnetic induction method is used for most of the products currently on the market. Inductive coupling WPT systems use receiver and transmitter coils for charging.

The power consumption of smartwatches is 288 mW [15] or 117.95 mW [16] at most. On the other hand, the peak power of a typical smartphone is over 2,000 mW at the maximum [17]. The power consumption of wearable devices in data transmission is 150–200 mW, and the peak power of smartphones is 3,500–4,000 mW [18]. Among the common wireless communication protocols used in IoT devices, Bluetooth has the lowest power, at 10 mW, while Wi-Fi has the highest power, at over 500 mW [19]. Moreover, the displays of smartphones and smartwatches consume power [20, 21]. Consequently, several heat dissipation methods for smartphones have been proposed [22, 23]. Although current smartwatches have comparatively low power due to their limited battery capacity, performance and functions on par with those of smartphones are expected in the near future.

Inductive coupling technologies have been actively researched for electric vehicles [24] and small electronic devices, including a wireless power system for mobile phones [25], a system for metal-cover smartphone applications [26], a charger for wearable devices [27], a battery-to-battery wireless system [28], and a bowl-shaped transmitting coil for hearables and wearables [29]. However, there has been no technical analysis of the heat dissipation effect of the receiver coil. In addition, there is no technical report of the heat dissipation effects of a receiver coil embedded inside a belt. The coil material is

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generally copper. We focused on the high thermal conductivity of the coil. In this letter, we propose a novel method to reduce temperatures at key hot spots of watch-type smart devices by using receiver coils for wireless charging. The key hot spots are the underside surface of a belt, the surface of the device body, and the ICs consuming the highest power. The most important spot is the belt's underside surface, since it is in direct contact with the skin of the human body for a long time.

In Section 2 of this letter, we present the proposed watch-type smart device. In Section 3, we show the heat dissipation effects of the proposed method on temperature reduction. In Section 4, we show the power transfer efficiency of the proposed method. In Section 5, we discuss the analysis results. Finally, Section 6 concludes with a brief summary of the letter.

2. Proposed watch-type smart device

Fig. 1 shows an overview of a proposed watch-type smart device. The wireless transfer method applied to such a device typically uses resonant coupling, which is accomplished by connecting capacitors to receiver and transmitter coils. The spiral coil for receiver is covered with dielectric material of silicon rubber. The coil was placed in the center of the belt thickness. The basic thickness, width, and length of the belt are 2 mm, 26 mm, and 200 mm, respectively. The coil conductor is wound with a spacing of 0.5 mm from the outside. The width and length of the placement area of the spiral coil are 24 mm and 160 mm, respectively.

Fig. 2 shows the structure of the device body. A printed circuit board (PCB) with a package (containing chips) above a battery is arranged. In the basic condition, the total power consumption is 1 W (0.14 W for the display and 0.86 W for the chips). An aluminum board is placed under the display. Table I lists the size and thermal conductivity of each part. The materials of the case and belt are polycarbonate and silicon rubber, respectively. Table II describes the coil conditions used in this letter. The width and thickness of the coil conductor are 1 mm and 0.5 mm, respectively. The spacing between conductors of the coil is 0.5 mm.

Fig. 1 Overview of proposed watch-type smart device.

Fig. 2 Structure of device body.

Table I Size and thermal conductivity of each part.

Part	Size (mm)	TC (W/mK)
Display	x = 30, y = 38, z = 2	x, y = 1.8, z = 0.1
Metal Plate	x = 30, y = 38, z = 0.3	237
Battery	x = 27, y = 35, z = 4	x, y = 15, z = 10
Case	x = 32, y = 40, z = 11	0.19
Belt	x = 26, y = 200, z = 2	0.2

Table II Coil conditions.

Item	Specification
Material	Copper (TC = 402 (W/mK))
Coil conductor cross section shape	Rectangle
Width and thickness of coil conductor	1 mm and 0.5 mm
Spacing between coil conductors	0.5 mm

3. Analysis of heat dissipation effects

In this section, we clarify the heat dissipation effects of the proposed method by performing thermal analysis using the multi-physics software Femtet [30].

In thermal analysis, the measurement points are “Display”, “IC”, and “Belt”, as shown in Fig. 3. “Display” indicates the point in the center of the surface of the display and is where the temperature on the surface becomes highest. “IC” indicates the point of the maximum temperature in the device body where heat generating sources are placed. “Belt” indicates the underside surface of the belt under the device body and is the point where the temperature in the place that touches the skin of the human body directly becomes highest. The most serious point is “Belt”. A low temperature burn may be caused here, since it touches the skin for a long time.

Fig. 3 Temperature measurement points.

3.1 Effect of belt coil width

Fig. 4 shows temperature changes when the belt coil width with the number of turns of a receiver coil was varied. As the number of turns of a receiver coil was varied from 1 turn to 8 turns, the belt coil width was varied from 3 mm to 24 mm. The belt coil length is 160 mm.

Fig. 5 shows the effect of heat dissipation due to

belt coil width. All temperatures for “Display”, “IC”, and “Belt” decreased as the number of turns (i.e. belt coil width) increased. When the number of turns was one (i.e. the belt coil width was 3 mm), the temperatures of “Display”, “IC”, and “Belt” were reduced by 47.4°C, 59.2°C, and 45.6°C (14.0%, 17.5%, and 42.6%) from 51.0°C, 66.5°C, and 60.9°C for a non-coil structure (i.e. the belt coil width was zero) in temperature rise to ambient temperature. When the number of turns was eight (i.e. the belt coil width was 24 mm), their temperatures were reduced to 42.4°C, 49.6°C, and 39.5°C (by 33.0%, 40.8%, and 59.7%). A notable point is that the temperature of “Belt” decreased significantly even when there was only one turn. The temperature reduction rates of 8 turns to 1 turn were 22.2%, 28.3%, and 29.7% at “Display”, “IC”, and “Belt”.

Fig. 4 Model for investigating effect of belt coil width.

Fig. 5 Effect of belt coil width.

3.2 Effect of belt coil length

Fig. 6 shows the belt coil length varied from 40 mm to 160 mm. The number of turns is eight. The length of the device body on the belt is also 40 mm.

Fig. 7 shows the characteristics of temperature vs. belt coil length. When the belt coil length was 40 mm (i.e. the coil embedded inside the belt under the device body), the temperatures of “Display”, “IC”, and “Belt” were reduced by 50.3°C, 65.0°C, and 59.3°C (2.8%, 3.6%, and 4.5%) to the structure without a coil. The effect of the coil on the temperature reduction is very small.

However, by changing the belt coil length from 40 mm to 160 mm, the temperatures of “Display”, “IC”, and “Belt” were reduced by 31.1%, 38.6%, and 57.8%. The belt coil length of 160 mm had a great effect on temperature reduction.

Fig. 6 Model for investigating effect of belt coil length.

Fig. 7 Effect of belt coil length.

3.3 Difference between plane and coil

Fig. 8(a) shows the copper plane embedded inside a belt. Fig. 8(b) shows the proposed coil in this letter, which is the copper spiral coil embedded inside a belt. The spacing between conductors of the spiral coil is 0.5 mm. The widths of the plane and the spiral coil including spacing are the same 24 mm.

Fig. 9 shows the temperature rise results when the plane and coil were embedded inside the belt. As we can see, the temperature reduction effects were almost identical. This demonstrates that the spiral coil is superior to the plane even if it is not used for wireless charging, since the weight can be reduced.

Fig. 8 Models for comparing (a) copper plane and (b) copper spiral coil embedded inside belt.

Fig. 9 Comparison of copper plane and copper spiral coil embedded inside belt.

3.4 Temperature distributions

Fig. 10 shows the temperature distributions for structures (a) without belt coil and (b) with belt coil (proposed). The total power consumption is 1 W, where the display consumes 0.14 W and ICs consume 0.86 W. The width and length of rubber belt are 26 mm and 200 mm. The width and length of the spiral coil built into the belt in Fig. 10(b) are 24 mm and 160 mm. the temperatures of “Display”, “IC”, and “Belt” were 51.0°C, 66.5°C, and 60.9°C for the structure without a coil, while the temperatures of “Display”, “IC”, and “Belt” were 42.4°C, 49.6°C, and 39.5°C for the structure of the proposed method. We can see that temperatures were reduced as a whole. In particular, the temperature of “Belt” (the key hot spot at the underside of the belt, which touches the skin directly) was significantly reduced.

Fig. 10 Temperature distributions: (a) without coil and (b) with coil embedded inside belt (proposed method).

4. Analysis of power transfer efficiency

We present the power transfer efficiency for the structure that used the proposed method. We utilized a magnetic resonant coupling wireless power transfer (MRC-WPT) system in this work. The resonant frequency was set to around 13.56 MHz. For the tuning, additional capacitors were used in the transmitter and receiver. The spiral coil of the receiver is 160 mm in length of the placement area. The spiral coil of the transmitter is 150 mm or 105 mm in length when the pitch is 2 mm or 9.5 mm, respectively.

An image of wireless charging for the proposed watch-type smart device is illustrated in Fig. 11. The receiver coil is embedded inside a belt made of silicon rubber. The self-inductance of the receiver coil (with width of 24 mm and length of 160 mm) is $5.07 \mu\text{H}$. The transmitter coil is embedded inside a case made of polycarbonate. The self-inductance values of the transmitter coils with pitches of 2 mm and 9.5 mm are $4.64 \mu\text{H}$ and $2.95 \mu\text{H}$, respectively.

Fig. 12 shows the maximum power transfer efficiencies when pitch was varied from 2 mm to 9.5 mm. The results were obtained using an electromagnetic analysis tool [30]. The pitch is the distance from the center to the center of coil conductors. As we can see, the system was able to obtain sufficient efficiency for

wireless charging even if the pitch was within 9.5 mm. When the pitches were 2 mm and 9.5 mm, the efficiencies were 93.1% and 91.1%, respectively.

Fig. 13 shows the frequency characteristics to the power transfer efficiency when the pitches were 2 mm and 9.5 mm. The transfer distance of the MRC-WPT system is longer than that of the traditional electromagnetic induction WPT system. When the resonance frequency shifted, power transfer efficiency decreased. In order to capture higher efficiency, it will be necessary to tune the capacitance (or inductance) and match the resonant frequencies.

Fig. 11 Image of wireless charging of proposed watch-type smart device.

Fig. 12 Maximum power transfer efficiency when pitch was varied.

Fig. 13 Frequency characteristics to efficiency at pitches of 2 mm and 9.5 mm.

5. Discussions

In this section, we discuss the analysis results describes in previous sections. In Sections 3.1 and 3.2, we presented that the width and length of the coil built into a belt have a great effect for heat dissipation. This is the reason why the area to dissipate heat is expanded by using a copper coil that thermal conductivity is very high. Especially, the temperature under the belt can be reduced by the belt coil.

On the other hand, from the result of width of 40 mm, the belt coil with the length only under the device body has almost no temperature reduction effect. This indicates that the receiver coil used for wireless charging of general smart watches has no heat dissipation effect.

From Section 3.3, we presented that the effects of the plane built into a belt and the coil built into a belt are almost identical. This is because the heat dissipation areas of the plane (e.g. mainly top and bottom) and the coil (e.g. top, bottom, and sides) are almost equal. The advantages of the coil to compare the plane are that it is light in weight and can be used for wireless charging.

From Section 3.4, we presented that the proposed method can reduce the temperature of the entire device. This is because the coil built into a belt becomes the heat dissipation path of the heat generation elements (IC and display).

From Section 4, we presented that the structure of the proposed method can get very high efficiency even when the pitch between a receiver coil and a transmitter coil was 9.5 mm. This is because the structures of the receiver coil and the transmitter coil placed on the back of the belt are almost similar and their coils can be get enough self-inductance values by utilizing a large area of the belt.

6. Conclusion

This letter presented a novel heat dissipation method for watch-type smart devices by utilizing a receiver coil for wireless charging. In general, coils used for wireless charging is made of copper that has very high thermal conductivity. The proposed method is achieved by embedding the copper receiver coil inside the belt. The analysis results showed that the proposed method had a significant effect on temperature reduction and enabled a good power transfer efficiency.

References

- [1] Market Data Forecast: Smartwatch Market (2021) <https://www.marketdataforecast.com/market-reports/smartwatch-market>.
- [2] D. Pal, *et al.*: "Quality of experience of smart-wearables: From fitness-bands to smartwatches," *IEEE Consumer Electronics Magazine* **9** (2019) 49 (DOI: 10.1109/MCE.2019.2941462).
- [3] E. Svertoka *et al.*: "State-of-the-art of industrial wearables: A systematic review," *COMM* (2020) 411 (DOI: 10.1109/COMM48946.2020.9141982).
- [4] F.J. Dian, *et al.*: "Wearables and the internet of things (IoT), applications, opportunities, and challenges: A survey," *IEEE Access* **8** (2020) 69200 (DOI: 10.1109/ACCESS.2020.2986329).
- [5] K. Suwannarat and W. Kurdthongmee: "Optimization of deep neural network-based human activity recognition for a wearable device," *Heliyon* **7** (2021) e07797 (DOI: 10.1016/j.heliyon.2021.e07797).
- [6] R.M. Al-Eidan, *et al.*: "A review of wrist-worn wearable: sensors, models, and challenges," *J. Sensors* **2018** (2018) 5853917 (DOI: 10.1155/2018/5853917).
- [7] R. Tortelli, *et al.*: "The use of wearable/portable digital sensors in Huntington's disease: A systematic review," *Parkinsonism & Related Disorders* **83** (2021) 93 (DOI: 10.1016/j.parkreldis.2021.01.006).
- [8] K. A. Walsh and D. Lin: "A smartwatch heart rate monitor prompts an unusual diagnosis," *JACC Case Reports* **2** (2020) 431 (DOI: 10.1016/j.jaccas.2019.11.087).
- [9] N. L. Pereria, *et al.*: "COVID-19: Understanding inter-individual variability and implications for precision medicine," *Mayo Clinic Proceedings* **96** (2021) 446 (DOI: 10.1016/j.mayocp.2020.11.024).
- [10] D. K. Ming, *et al.*: "Continuous physiological monitoring using wearable technology to inform individual management of infectious diseases, public health and outbreak responses," *IJID* **96** (2020) 648 (DOI: 10.1016/j.ijid.2020.05.086).
- [11] Y. Guo, *et al.*: "A review of wearable and unobtrusive sensing technologies for chronic disease management," *Computers in Biology and Medicine* **129** (2021) 104163 (DOI: 10.1016/j.combiomed.2020.104163).
- [12] Magnetic resonant method of wireless power transfer technology for industrial equipment: TDK Corporation <https://product.tdk.com/info/en/techlibrary/developing/wireless/index.html>.
- [13] A. Kurs, *et al.*: "Wireless power transfer via strongly coupled magnetic resonances," *Science* **317** (2007) 83 (DOI: 10.1126/science.1143254).
- [14] X. Lu, *et al.*: "Wireless charging technologies: Fundamentals, standards, and network applications," *IEEE Commun. Surveys Tuts.* **18** (2016) 1413 (DOI: 10.1109/COMST.2015.2499783).
- [15] K. Wu, *et al.*: "Power saving and secure text input for commodity smart watches," *IEEE Trans. Mobile Comput.* **20** (2021) 2281 (DOI: 10.1109/TMC.2020.2976007).
- [16] X. Sun, *et al.*: "ActDetector: Detecting daily activities using smartwatches," *MASS* (2017) 1 (DOI: 10.1109/MASS.2017.35).
- [17] G. P. Perucci, *et al.*: "Survey on energy consumption entities on the smartphone platform," *VTC Spring* (2011) 5956528 (DOI: 10.1109/VETECS.2011.5956528).
- [18] M. Satyanarayanan, *et al.*: "The computing landscape of the 21st century," *HotMobile '19: the 20th International Workshop on Mobile Computing Systems and Applications* (2019) 45 (DOI: 10.1145/3301293.3302357).
- [19] Energy harvesting technologies for IoT edge devices: IEA 4E (2018) <https://www.iea-4e.org/>.
- [20] Y. Choi, *et al.*: "Fully automated OLED display power modeling for mobile devices," *PMC* **50** (2018) 41 (DOI: 10.1016/j.pmcj.2018.07.006).
- [21] M.R. Fernandez, *et al.*: "Review of display technologies focusing on power consumption," *Sustainability* **7** (2015) 10854 (DOI: 10.3390/su70810854).
- [22] H. Tang, *et al.*: "Review of applications and developments of ultra-thin micro heat pipes for electronic cooling," *Applied energy* **223** (2018) 383 (DOI: 10.1016/j.apenergy.2018.04.072).
- [23] M.S. Ahamed, *et al.*: "Characterization of a high performance ultra-thin heat pipe cooling module for mobile hand held electronic devices," *Heat mass transfer* **53** (2017) 3241 (DOI: 10.1007/s00231-017-2022-7).
- [24] D. Kim, *et al.*: "Electric parameter tuning of wireless power transfer coil for charging interoperability of electric vehicles," *IEEE EMCSI* (2020) 619 (DOI: 10.1109/EMCSI38923.2020.9191578).
- [25] P.S. Riehl, *et al.*: "Wireless power systems for mobile devices supporting inductive and resonant operating modes," *IEEE Trans. Microw. Theory Techn.* **63** (2015) 780 (DOI: 10.1109/TMTT.2015.2398413).
- [26] J.-Q. Zhu, *et al.*: "Three-coil wireless charging system for metal-

- cover smartphone applications,” IEEE Trans. Power Electron. **35** (2020) 4847 (DOI: 10.1109/TPEL.2019.2944845).
- [27] R.-C. Kuo, *et al.*: “A 3D resonant wireless charger for a wearable device and a mobile phone,” IEEE WPTC (2015) 7140169 (DOI: 10.1109/WPT.2015.7140169).
- [28] M. Huang, *et al.*: “A reconfigurable bidirectional wireless power transceiver for battery-to-battery wireless charging,” IEEE Trans. Power Electron. **34** (2019) 7745 (DOI: 10.1109/TPEL.2018.2881285).
- [29] J. Kim, *et al.*: “Free-positioning wireless charging system for hearing aids using a bowl-shaped transmitting coil,” IEEE Trans. Microw. Theory Techn. **63** (2015) 791 (DOI: 10.1109/TPEL.2018.2881285).
- [30] Femtet® 2020.0: Murata Software Co., Ltd. (2020) <http://www.muratasoftware.com/en>.