A Low-Loss and Compact UHF RFID Tag Antenna for Implanted Denture

Junyi Xu, Hiroyasu Sato, *Member, IEEE*, Mizuki Motoyoshi, *Member, IEEE*, Noriharu Suematsu, *Senior Member, IEEE*, Kazuhito Yasui, and Qiang Chen, *Senior Member, IEEE*

***Abstract*—A denture implanted UHF RFID tag antenna is proposed. The limitation on antenna size means that a low-loss and compact antenna including matching circuit is necessary to increase the tracking distance. To reduce the loss brought by reflection, a partially exposed folded dipole antenna with gamma matching is utilized. The denture implanted RFID tag is fabricated by using materials utilized in the exact denture such as metal wire and resin. Furthermore, the RFID operation properties of the denture implanted tag are evaluated by changing the parameters of antenna structure. Based on the measurement result, the new proposed structure reduce the reflection loss from the mismatch between RFID chip and small antenna, which provides enough energy for communication. Also, this proposed antenna structure provides a brand new idea for designing antenna in medium.**

***Index Terms*—RFID, denture, compact, low-loss, partially exposed, HBEL, resin.**

I. Introduction

WIRELESS body area network (WBAN) devices [1] including wearables and implants have gradually become the main trend of biomedical electronic devices in the current and future development because of its convenient use and various functions. In order to care for the disabled elderly, in recent years, many wearable devices such as hand ring have been developed. However, due to the fact that wearable devices are easy to be lost, and that the old people often feel sick with the bondage brought by the wearable devices, it is very difficult to be used successfully in the practice. Therefore, in this study, we are committed to implant the device into the dentures, which most of the elderly need daily, with Radio Frequency Identification (RFID) technology known as one of wireless communication technologies [2]. The presence of the human body in close proximity to the RFID device creates challenges in terms of antenna design. There are two main tasks when designing such an implanted antenna. First, the antenna size must be reduced to be implanted inside the human body. Also, because the loss of the surrounding biological tissues can not be ignored, the power can be used is limited. In addition, the presence of passive RFID system will bring round-trip transmission loss, which must be taken into account.

To deal with those problems occurred in the design of implanted antennas, there have been several researches yet now. Practical capsule endoscopes have been developed with the built-in button battery to drive a CCD camera for taking pictures of the inside body [3]. After all it was dangerous to swallow a battery into the body, an inner-Layer capsule dipole antenna for ingestible endoscope at 500 MHz is proposed [4]. The antenna was isolated from the external tissues with de-ionized water. In this way, the dielectric loss due to the lossy tissue was reduced. And because of the de-ionized water isolation layer, the antenna was designed in much smaller geometry size due to the high permittivity of the water. However, in Li's previous research [5], when shortening the length of the antenna, the power transmission at the resonance frequency decreased. Therefore, at UHF band the loss from such as impedance matching need to be low enough, otherwise the received power at the RFID chip may be too small to drive the chip. In [6] sensors were implanted beneath the scalp which acted as a part of BMI (Brain-Machine Interface) technology. The whole system was composed of an implanted antenna driving the electrodes and an on-body transmit antenna supplying power to the implanted antenna. In our case, it is difficult to stick an on-body transmit antenna outside the cheek. Also, the implanted antenna and electrodes proposed in [6] are fully in contact with the tissue and liquid in the skull, which brings considerable loss. Finally in [7] a folded dipole implanted antenna covered by full glass coating to reduce the loss from the external tissue at 2.45 GHz was proposed. Due to the full glass coating, the resonance frequency significantly changed when the size of the glass coating varied. However, in our application, the antenna design needs to be denture-tolerant. Therefore, the variable denture size is necessary for different customers while keeping a stable resonance frequency of implanted antenna.

As mentioned above, all of those previous researches were carried out in such environment with no strict limitation on antenna size. However in our case, the antenna needs to be designed in a limited volume. Therefore, an efficient and

Manuscript received March 17, 2021; revised April 28, 2021; accepted May 7, 2021. Date of publication May 19, 2021; date of current version December 27, 2021. This work was supported by JST Center of Innovation Program under Grant JPMJCE1303, and in part by the WISE Program for AI Electronics, Tohoku University. *(Corresponding author: Junyi Xu.)*

Junyi Xu is with the School of Engineering, Tohoku University, Sendai 980-8579, Japan (e-mail: xu-j@ecei.tohoku.ac.jp).

Hiroyasu Sato is with the School of Engineering, Tohoku University, Sendai 980-8579, Japan (e-mail: sahiro@ecei.tohoku.ac.jp).

Mizuki Motoyoshi and Noriharu Suematsu are with the Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan (e-mail: mizuki@riec.tohoku.ac.jp; suematsu@riec.tohoku.ac.jp).

Kazuhito Yasui is with the Cosmotechs Ltd., Tomiya 981-3361, Japan (e-mail: cosmotechs.ltd.yasui@gmail.com).

Qiang Chen is with the Department of Communications Engineering, Tohoku University (Aobayama Campus), Sendai 980-8579, Japan (e-mail: chenq@ecei.tohoku.ac.jp).

Digital Object Identifier 10.1109/JRFID.2021.3081183

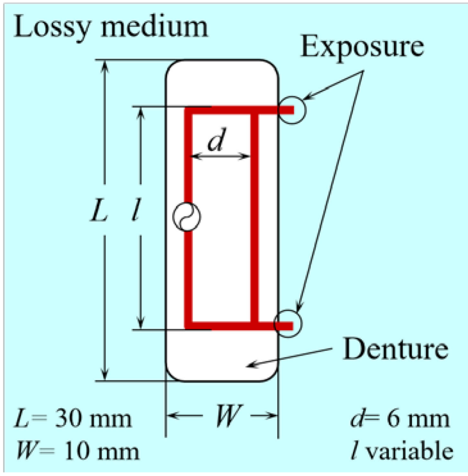


Fig. 1. Design of the UHF RFID tag antenna for implanted denture.

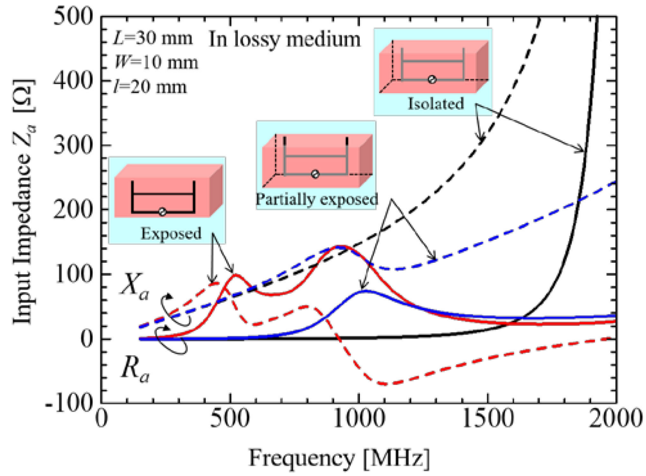


Fig. 2. Impedance of exposed type, isolated type and partially exposed antenna when placed in HBEL.

compact antenna is necessary for implanted RFID tag antenna. The main problem to be solved is that, in order to reduce power loss due to the small antenna structure, the conjugate impedance matching between the antenna and RFID chip in the body have to be realized. Traditionally, there are basically two types of in-body antennas: antenna isolated from the tissue and the one exposed to the tissue. For the isolated antenna, the resistance is approximately zero so that it is hardly possible to meet the impedance matching condition unless a lossless matching circuit is utilized. And for totally exposed antenna, although the resistance can be influenced by the medium, it is challenging to reduce the power loss in the human body.

In this paper, an RFID tag antenna implanted in the denture using UHF band is proposed. With those factors mentioned above in mind, a partially exposed folded dipole antenna with gamma matching is utilized. The folded structure reduces the size of the antenna. And the exposure and the gamma matching make the impedance easy to match with RFID chip impedance. Also, the partially exposed antenna decreases the conductive loss from the contact with the lossy medium. Also the proposed antenna is not sensitive to the change of denture size, which means bulk production, low cost and low difficulty for dental technicians.

To evaluate the antenna, the structure design using denture materials and the results of RFID tag operation are presented. In Section II, the antenna design is described. The differential mode S-parameter method [4] will be used for broadband measurement of input impedance in surrounding biological tissues equivalent liquid. The impedance measurement and reflection coefficient calculation will be presented. Section III describes the evaluation of denture implanted RFID tag. The RFID tag with a RFID chip mounted on the prototype antenna is manufactured experimentally. The tag performance by measuring the received signal strength indication (RSSI) will be presented.

II. Antenna Design

With reference to Fig. 1, the design of partially exposed dipole antenna for denture implanted UHF RFID tag antenna is proposed. Folded dipole is the main part of the proposed antenna. Gamma matching circuit is utilized to reduce the power reflection due to mismatching. The antenna is placed in acrylic resin block as denture mode with conductor partially exposed to the surrounding tissue.

Fig. 2 shows the input impedance of three different implant antennas with the same geometry, including the above mentioned two basic types and the proposed one. For the isolated antenna, the resistance is approximately zero so that it is hardly possible to meet the impedance matching condition unless a lossless matching circuit is utilized. It can be observed that the resistance of the exposed antenna and the partially exposed antenna increase. As for the reason, the resonant frequency decreases owing to the effect of high permittivity surrounding. Concurrently, because of the wavelength shortening effect of the surrounding tissue, the size of the exposed antenna can be reduced so that it is possible to be implanted into denture. However, the totally exposed antenna shows the characteristics of high loss, because the antenna wire fully touches the lossy surrounding tissues. Therefore, combining the merits of both the isolated and fully exposed antenna, a partially exposed structure is proposed, in which the antenna wire ends exposed partially from its protecting lossless coating into the outside lossy one. Compared to the isolated antenna, the fully and partially exposed types are in contact with the lossy medium so that there is a conductive current in the liquid which increases the antenna resistance. It can be observed that the wavelength can also be shortened by the influence of the external high permittivity medium just by using the partially exposed structure. Although it does bring additional loss due to the exposure, the size reduction of the antenna will be more beneficial to current denture antenna implantation application. Furthermore, as shown in Fig. 3, the change of the denture volume, can hardly affect the matching condition, which means that proposed designed has the characteristic of denture-tolerant.

As seen from Fig. 4, the measurement model of designed UHF band RFID tag antenna for denture implantation is shown. For impedance matching, the dipole antenna with the gamma matching structure is utilized, where both ends of the gamma-matched dipole antenna partially reach out the denture and contact with the lossy human tissue [8]. The antenna

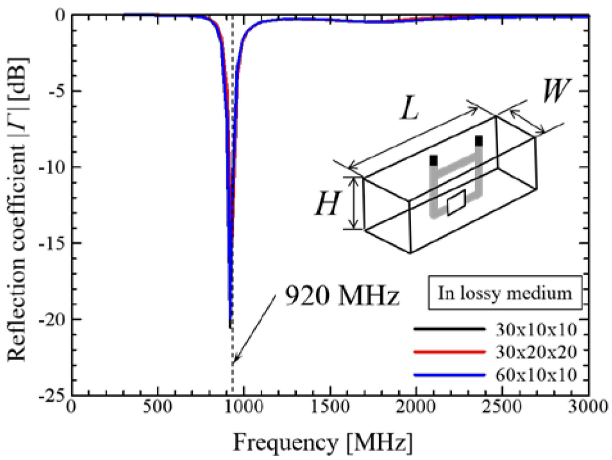
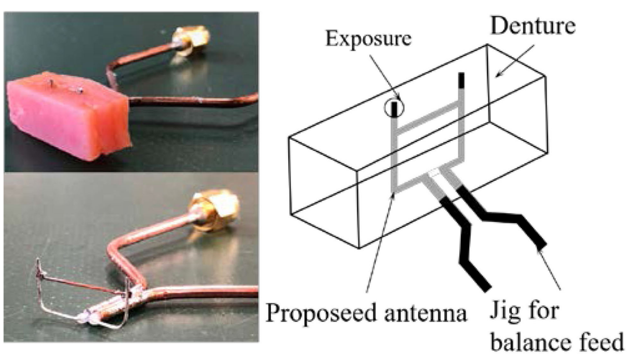
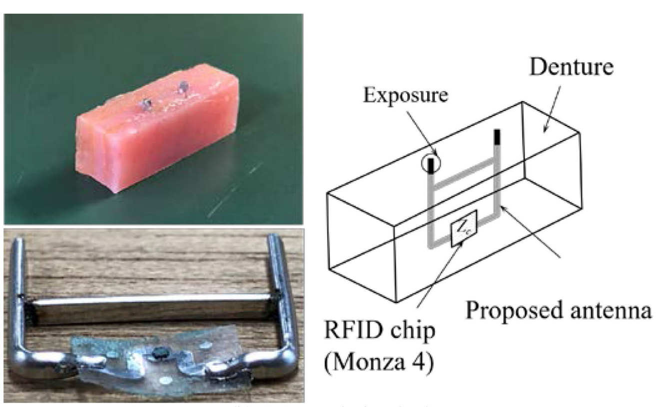


Fig. 3. Reflection coefficient of denture implanted RFID tag antenna with different volume of resin block.



(a) Antenna design (jig)



(b) Antenna design (tag)

Fig. 4. Two structures used in different measurement (impedance evaluation and RSSI evaluation).

conductor made of copper wire is fixed by inserting it into a resin block with a volume 30(L) × 10(W) × 10(W) mm^3. To achieve the gamma matching, a shorted line (length l variable, distance with the dipole $d = 6$ mm is attached to the folded dipole.

A jig structure shown in Fig. 4(a) is used. It is necessary when measuring the input impedance of the designed antenna by using the network analyzer, because it is impossible to evaluate the matching condition between RFID chip and antenna after attaching the chip to the antenna. On the other hand, when evaluating the performance of the designed RFID tag

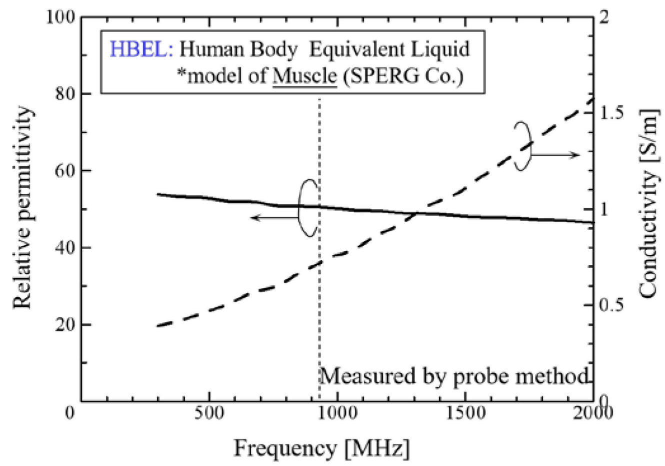


Fig. 5. Relative permittivity and conductivity of HBEL.

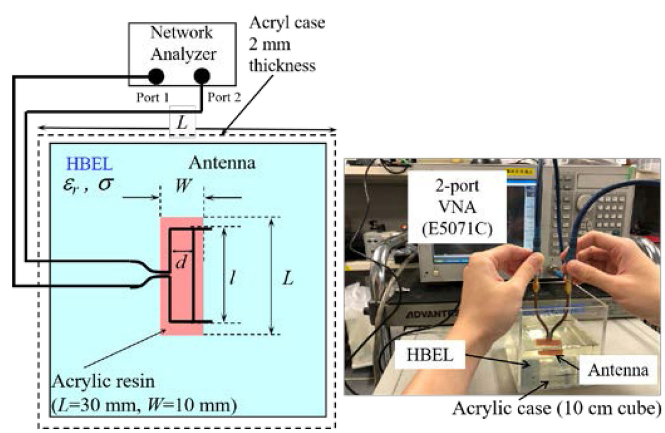


Fig. 6. Experimental setup for impedance measurement.

by measuring received signal strength indication (RSSI), the structure shown in Fig. 4(b) should be used.

Due to impedance step-up theory [10], a lot of parameters can affect the matching condition, such as the thickness of the line and the distance between the short line and the dipole antenna. In this article, only the length of the short line l is chosen as variable, which has relatively more space to adjust.

With the model proposed in Fig. 4(a), four kinds of trial antennas with different length l were fabricated. In the experiment, to realize the human tissue, SPEAG's surrounding biological tissues equivalent liquid (HBEL) with complex permittivity and conductivity of muscle shown in Fig. 5 is utilized, where the medium parameters are measured by the coaxial probe method. The relative permittivity of acrylic resin used as the coating to fix the antenna is also measured by the coaxial probe method.

Fig. 6 shows the experiment setup. The RFID tag antenna shown in Fig. 1 is placed in the center of a square cubic acrylic case (150x150x150 mm^3). As a phantom, SPEAG's human body equivalent liquid (HBEL) with complex permittivity and conductivity of muscle ($\varepsilon_r = 58$, $\sigma = 0.7$ S/m, @920MHz) is filled in the cubic case. In order to evaluate the input impedance of the antenna over a wide band by the 2-port VNA (Agilent E5071C), the differential mode S-parameter

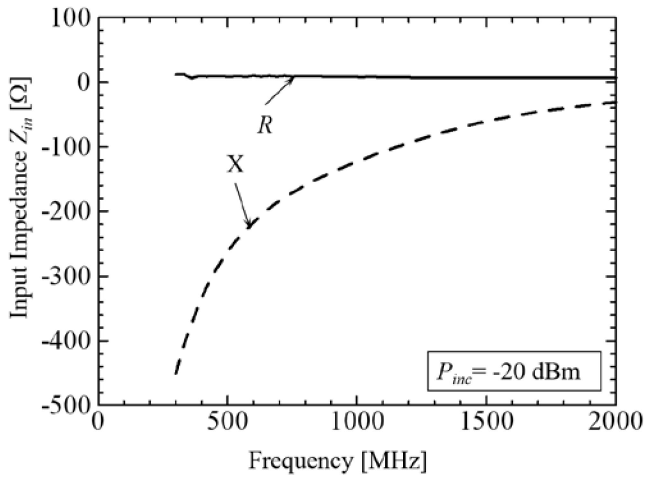


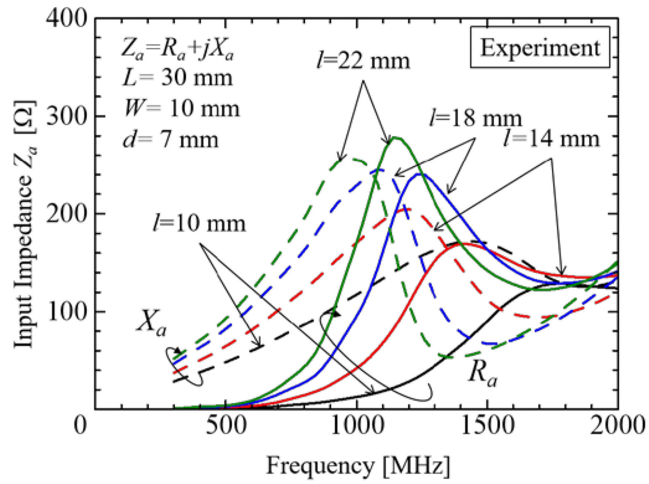
Fig. 7. Frequency characteristic of RFID chip Monza-4 impedance measured by impedance analyzer.

method [5] is used. On the other hand, an impedance analyzer is used to measure the input impedance of the RFID chip Monza 4 (Impinj) [9]. Because the size of the RFID chip is very small, in order to lower the complexity of measurement, when cutting out the chip from the RFID tag on the market, a little bit of conductor line is reserved. The frequency characteristic of the chip impedance is shown in Fig. 7. The chip impedance at 920 MHz with the incident power of −20 dBm is $Z_c = 8.8 - j131\ \Omega$. In this case, an antenna with small resistance and large inductance is necessary.

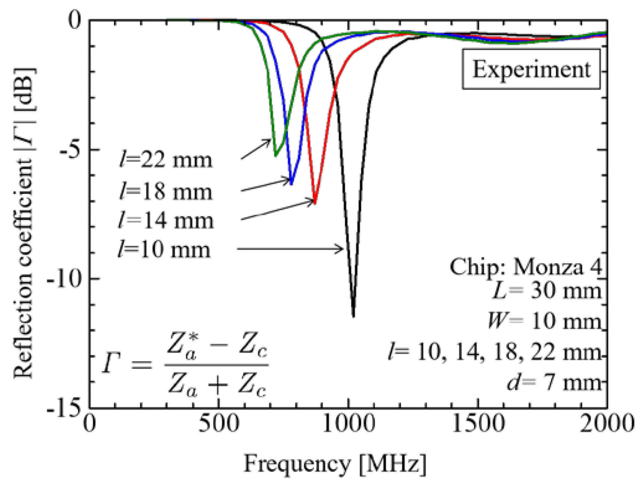
Fig. 8(a) shows the frequency characteristics of the input impedance when l is varied from 10 mm to 22 mm. The anti-resonance frequency and increased resistance are observed at frequencies from 1 GHz to 1.5 GHz. Also, it can be observed that, the antenna impedance $Z_a = 7.6 + j105\ \Omega$ when the length of shorted line $l = 10$ mm, and $Z_a = 27 + j152\ \Omega$ when $l = 14$ mm. Fig. 8(b) shows the reflection coefficient calculated according to the characteristic impedance Z_c of the RFID chip measured by an impedance analyzer. Obviously, from this result, it is possible to obtain conjugate matching at 920 MHz when the length of the shorted wire l is around 12 mm.

However, the structure shown in Fig. 4 is not the most suitable one for denture use. The sharp exposure might hurt the oral mucosa. Therefore, the results are simulated when the sharp exposures are replaced by two square plates as shown in Fig. 9. Fig. 10(a) shows the frequency characteristics of the input impedance when l is varied from 6 mm to 18 mm. And Fig. 10(b) shows the reflection coefficient calculated according to the characteristic impedance Z_c of the RFID chip. It can be seen that the inductance provided by the plate exposure changes the impedance matching state with the RFID chip. But it is possible to adjust the length of the shorted line l to achieve the impedance matching, just like that when the sharp exposure structure is utilized.

Fig. 11 shows the frequency characteristics of the input impedance and reflection coefficient with different area of the exposed plate. It can be seen that bigger plate will provide larger inductance to influence the matching condition. In this



(a) Frequency characteristics of denture implanted RFID tag antenna impedance (experiment)



(b) Reflection coefficient of denture implanted RFID tag antenna (antenna and chip impedance are both experiment value.)

Fig. 8. Experiment results.

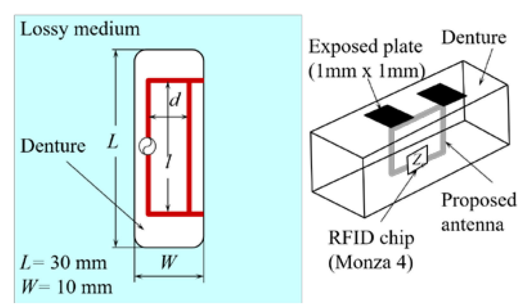
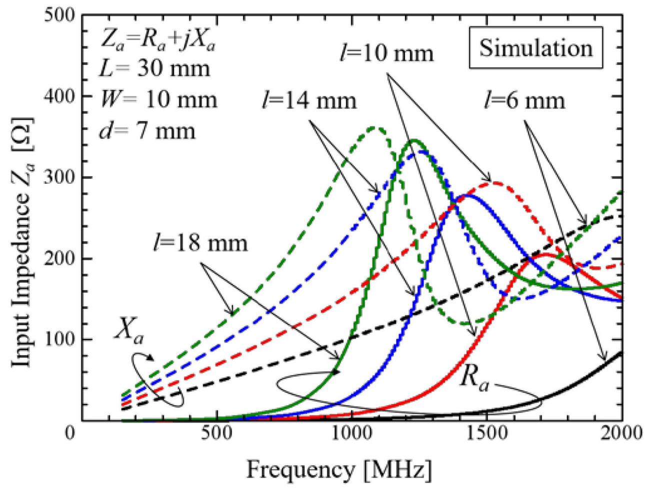


Fig. 9. Experimental setup for RSSI measurement.

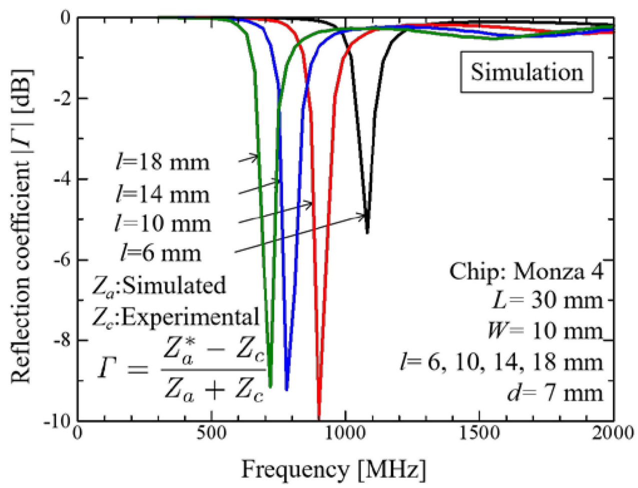
case, a capacitance is necessary which will increase the complexity of the structure in the limited denture. Therefore, it seems better just to flatten the exposed ends with as smaller areas as possible.

III. Evaluation of Denture Implanted RFID Tag

Impedance matching is not the only condition should be satisfied, but also the transmission condition. The structure

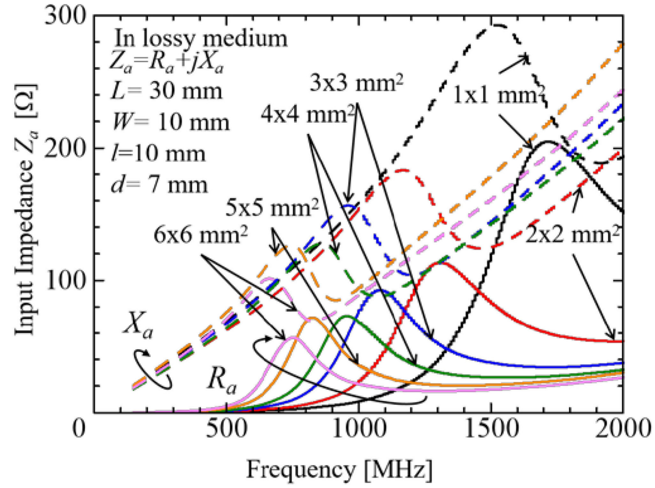


(a) Frequency characteristics of denture implanted RFID tag antenna impedance with plate exposure (simulation)

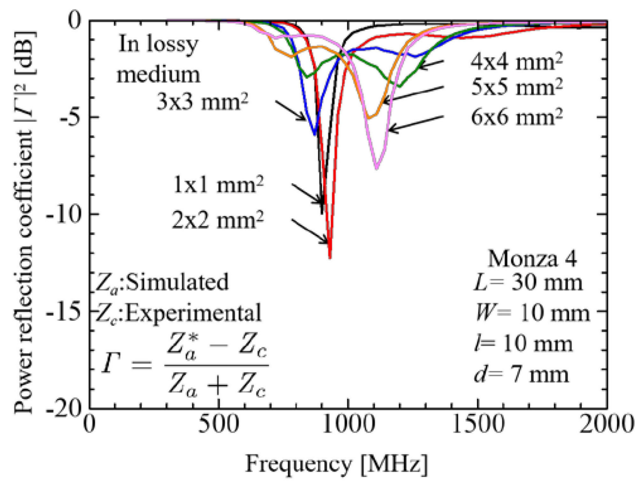


(b) Reflection coefficient of denture implanted RFID tag antenna with plate exposure (antenna impedance is simulation value and chip impedance is experiment value.)

Fig. 10. Simulation results of 1 mm^2 plate exposure.



(a) Frequency characteristics of denture implanted RFID tag antenna impedance with different plate exposure (simulation)



(b) Reflection coefficient of denture implanted RFID tag antenna with plate exposure (antenna impedance is simulation value and chip impedance is experiment value.)

Fig. 11. Simulation results of different plate exposure.

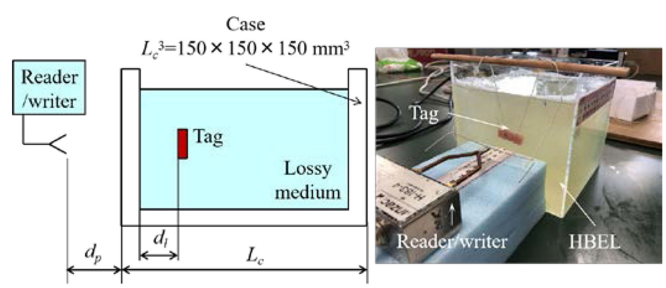


Fig. 12. Experimental setup for RSSI measurement.

shown in Fig. 4(b) of the prototype implanted denture RFID tag were fabricated for evaluation. The dipole antenna and the shorten line are made of dental stainless steel wire (mainly iron, chromium and nickel). Then denture implanted RFID tag is manufactured by fixing the design antenna with the RFID chip into the denture fixing material resin. The short-circuit wire of the antenna conductor is welded to the folded dipole using laser welding, a slit is cut at the feed part of the dipole using a router, and the RFID chip is stripped from a commercially available RFID tag including a little bit transmission line attached.

Fig. 12 shows an experimental system for measuring received signal strength indication (RSSI). Prototype denture implanted RFID tag is placed in a cubic acrylic case (150x150x150 mm^3) filled with HBEL at a distance of d_l = 20 mm from the surface, and a folded dipole antenna with a hybrid is used as the receiving antenna for the reader/writer with the distance d_p from the surface. This is based on the assumption that the cheek thickness is about 20 mm and that a hand-held reader/writer is placed near the cheek. As for the reader/writer, JIS U524R 4CH UHF Multi-Scanner by Japan Information System is utilized.

In order to confirm the validity of the design for the length l, the RSSI is measured when l varies from 9 mm to 15 mm. Fig. 13 shows the RSSI when d_l = 20 mm. In the vicinity of l = 13 mm, RSSI is large enough and the best response is obtained. It can be concluded that the conjugate impedance

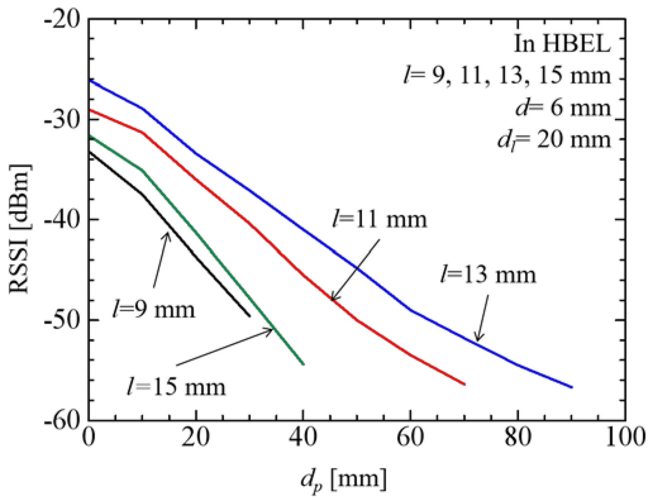


Fig. 13. d_p characteristics of RSSI when l varied.

matching condition is established near $l = 13$ mm, and this value almost coincides with the design value $l = 12$ mm obtained in Section III. With the suitable design length of l, when the folded dipole is chosen as the reader/writer antenna, a response distance of around 90 mm can be obtained. Other reader/writer antennas with higher gain can be used to increase the response distance, since it is difficult to decrease the loss of the human tissue.

In addition, from Fig. 13, it can be observed that, when l varied, the response at the reader/writer is always interrupted once the RSSI reaches about −55 dBm. Clearly, it can be concluded that the sensitivity of the RFID chip made the interruption. The RFID chip used in this case is Impinj's Monza4. According to the data sheet of Monza4, its sensitivity is −17.4 dBm. Then the one-way propagation loss is 37.6 dB, so the round trip one is 75.2 dB. Therefore, the required reader/writer input power in this case should be 20.2 dBm. Considering the mismatch loss and the signal processing loss, it is possible that the response will be interrupted when RSSI is near −55 dBm, for the experimental input power is about 30 dBm. In order to obtain a larger response distance, an easy and direct method is to use a RFID chip with higher sensitivity.

IV. Conclusion

An RFID tag antenna implanted in the denture using UHF band was proposed. As for the antenna design, a partially exposed folded dipole antenna with gamma matching was utilized. The folded structure reduced the size of the antenna. And the exposure and the gamma matching made the impedance easy to match with RFID chip impedance. Also, the partially exposed antenna decreased the conductive loss from the contact with the lossy medium which made the antenna efficient. Concurrently, proposed partially exposed folded dipole antenna had the characteristic of denture-tolerant to meet the requirement from different user. In conclusion, it was found that the proposed structure provided the possibility on designing a low-loss and compact implanted antenna.

References

[1] R. Schmidt, T. Norgall, J. Mörsdorf, J. Bernhard, and T. von der Grün, "Body area network BAN—A key infrastructure element for patient-centered medical applications," *Biomedizinische Technik*, vol. 47, no. S1, pp. 365–368, 2002.

[2] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication*. Chichester, U.K.: Wiley, 2010.

[3] G. Iddan, G. Meron, A. Glukhovsky, and P. Swain, "Wireless capsule endoscopy," *Nature*, vol. 405, no. 6785, p. 417, May 2000.

[4] H. Sato, Y. Li, J. Xu, and Q. Chen, "Design of inner-layer capsule dipole antenna for ingestible endoscope," in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Busan, South Korea, Oct. 2018, pp. 1–2.

[5] H. Sato, Y. Li, and Q. Chen, "Experimental study of transmission factor through conducting surrounding biological tissues equivalent liquid," in *Proc. Int. Symp. Antennas Propag. (ISAP)*, Okinawa, Japan, 2016, pp. 990–991.

[6] E. Moradi *et al.*, "Miniature implantable and wearable on-body antennas: Towards the new era of wireless body-centric systems [antenna applications corner]," *IEEE Antennas Propag. Mag.*, vol. 56, no. 1, pp. 271–291, Feb. 2014.

[7] H. Lin, M. Takahashi, K. Saito, and K. Ito, "Design of miniature implantable tag antenna for radio-frequency identification system at 2.45GHz and received power analysis," *IEICE Trans. Commun.*, vol. E97, no. 1, pp. 129–136, 2014.

[8] H. Sato and Q. Chen, "Partially exposed capsule dipole antenna in lossy liquid," in *Proc. IEICE Soc. Conf.*, Sep. 2018, Art. no. B-1-114.

[9] "Monza 4 tag chip datasheet," Impinj, Inc., Seattle, WA, USA, Data sheet. Accessed: Jan. 2015. [Online]. Available: https://support.impinj.com/hc/en-us/articles/202756908-Monza-4-RFID-Tag-Chip-Datasheet

[10] Y. Mushiake, "An exact step-up impedance-ratio chart of a folded antenna," *Trans. IRE Prof. Group Antennas Propag.*, vol. 2, no. 4, pp. 163–163, Oct. 1954, doi: 10.1109/T-AP.1954.27992.

Junyi Xu received the bachelor's degree in electronic engineering from the Beijing Institute of Technology University, Beijing, China, in 2017, and the master's degree in electronic engineering from Tohoku University, Sendai, Japan, in 2020, where he is currently pursuing the Ph.D. degree. His research interests include antenna design and antenna characteristics in lossy medium.

Hiroyasu Sato (Member, IEEE) received the bachelor's and master's degrees from Chuo University, Tokyo, Japan, in 1993 and 1995 respectively, and the Ph.D. degree from Tohoku University, Sendai, Japan, in 1998.

He is currently an Assistant Professor with the Department of Electrica Communications, Tohoku University. His areas of interests include computational electromagnetics, antennas in plasma, antennas for plasma production, broadband antennas, and millimeter wave imaging. He is a member of the Institute of Electronics, Information and Communication Engineers.

Mizuki Motoyoshi (Member, IEEE) was born in Tokyo, Japan, 1982. He received the B.E. degree from Sophia University, Japan, in 2005, the M.E. and Ph.D. degrees in electronics engineering from the University of Tokyo, Japan in 2007 and 2011, respectively. From 2014 to 2021, he had been an Assistance Professor with the Research Institute of Electrical Communication, Tohoku University. Since 2021, he has been an Associate Professor with the Shizuoka Institute of Science and Technology. His research interests are on RFCMOS design and modeling for millimeter-wave wireless Communication. He received the Young Researcher's Award in 2007 in IEICE.

Noriharu Suematsu (Senior Member, IEEE) was born in Tokyo, Japan, in 1962. He received the B.S., M.S.,and Dr. Eng. degrees in electronics and communication engineering from Waseda University, Tokyo, Japan, in 1985, 1987, and 2000, respectively. In 1987, he joined Mitsubishi Electric Corporation, Kanagawa, Japan, where he was engaged in research and development on microwave and millimeter-wave solid-state circuits, including Si monolithic microwave integrated circuits, linearizers, transceivers for cellular phones, ITS, and satellite communication systems. From 1992 to 1993, he was a Visiting Researcher with the University of Leeds, Leeds, U.K. Since 2010, he has been a Professor with the Research Institute of Electrical Communication, Tohoku University, Sendai, Japan. His current interests are in next generation broad-band wireless transceivers and systems for terrestrial and satellite communications. He was a recipient of the Shinohara Award from the Institute of Electronics Information and Communication Engineers (IEICE) in 1992, the Ohm Award from the Promotion Foundation for Electrical Science and Engineering in 2002, the Prize for Science and Technology (Development Category) of the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology, Japan in 2009, and the IEICE Electronic Society Award in 2012. He is a Fellow of the IEICE, Japan.

Kazuhito Yasui received the bachelor's degree from Seigakuin University, Japan, in 2004, and the graduated degree in dental technician from Tohoku Dental Technology Professional Training College, Sendai, Japan, in 2009. He is currently the General Manager of Cosmotechs Ltd.

Qiang Chen (Senior Member, IEEE) received the B.E. degree from Xidian University, Xi'an, China, in 1986, and the M.E. and D.E. degrees from Tohoku University, Sendai, Japan, in 1991 and 1994, respectively, where he is currently a Chair Professor with the Electromagnetic Engineering Laboratory, Department of Communications Engineering, Faculty of Engineering. His primary research interests include antennas, microwave and millimeter wave, electromagnetic measurement, and computational electromagnetics. He received the Best Paper Award and the Zen-ichi Kiyasu Award in 2009, from the Institute of Electronics, Information and Communication Engineers (IEICE). He served as the Chair of IEICE Technical Committee on Photonics-Applied Electromagnetic Measurement from 2012 to 2014, the IEICE Technical Committee on Wireless Power Transfer from 2016 to 2018, and the IEEE Antennas and Propagation Society Japan Chapter from 2017 to 2018. He is currently the Chair of IEICE Technical Committee on Antennas and Propagation, and a Fellow of IEICE.