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研究課題名（和文）Metamaterial-based Compact and Efficient Wireless Power Transfer System for Biomedical Implants

研究課題名（英文）Metamaterial-based Compact and Efficient Wireless Power Transfer System for Biomedical Implants

研究代表者
Pokharel　R. K.　(Pokharel, Ramesh)

九州大学・システム情報科学研究院・教授

研究者番号：60398568

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研究成果の概要（和文）：本研究では、小型化ワイヤレス電力伝送（WPT）システムの新たな構造と、そのWPTシステムの伝送距離およびアラインメントの改善のために、新たなメタマテリアルの設計手法を提案し、フォントムを使った実験結果と比較により、その設計手法と開発したシステムの有効性を確認した。また、整流回路を受信機に集積する新たな方法を提案し、サイズを増やさずに効率を維持し、7mm x 7mmの受信機を使用して、ACからDCへの変換効率が35%に超えることに成功した。

研究成果の学術的意義や社会的意義
Rechargeable or battery-free medical implants, like tiny batteries for pacemakers, promise minimally invasive surgeries and wireless communication for easy follow-up. This solution aims to reduce costs from repeated surgeries, improve life quality, and minimize emergencies and insurance expenses.

研究成果の概要（英文）：In this project, we developed a novel structure for a compact wireless power transfer (WPT) system and an innovative metamaterial to enhance power transfer efficiency, WPT distance and misalignment through human tissue. We have also proposed an innovated way to integrate the rectifier circuits on receiver so that its size is not increased with sacrificing its efficiency. Using a 7mm x 7mm receiver, we achieved an AC to DC efficiency of over 35%.

研究分野：Electronic

キーワード：metamaterial　WPT system　SWIPT system　embedded absorber　data rate　compact size

１．研究開始当初の背景

Ensuring continuous tracking of human health information is necessary to ensure a better life through early detection of abnormalities or diseases. Hence, necessary measures can be taken to secure health services that guarantee appropriate treatment. Biomedical sensors/implants can monitor and track the vital signs of the human body to achieve this target. A fundamental requirement of such sensors is the size's compactness to ensure the treated person's comfort. Another issue is that replacement surgery may be necessary to replace the implanted IoT sensor due to battery failure. Therefore, the essential energy for the operation of these IoT sensors can be supplied externally by exploiting wireless power transfer (WPT) technology to a miniaturized receiver attached to an IoT sensor. Hence, WPT technology can overcome the battery limitations. Still, the human body is considered a harsh environment for WPT, and three problems do exist: (i) resonance mismatch, (ii) quality factor degradation, and (3) receiver bulkiness. Here, solutions are proposed to overcome these problems using a new design theory for a compact inductor’s model using novel stacked metamaterials.

２．研究の目的

The main purpose of this research is to realize a compact and high-efficiency WPT system through biological tissues (phantom), which is inherent to realizing a battery-less IoT sensor/implants for future biomedical applications. First, a new design theory for compact inductors will be proposed, which is not affected by the dielectric property of the tissues. A new metamaterial will also be proposed, with its unit cells stacked. The originality of this configuration appears in its capability to overcome the resonance mismatch and quality factor degradation issues in the conventional WPT system. The reasons are (i) the proposed compact inductors have minimum or no effect on its capacitive parts due to the biological tissues, (ii) the proposed stacked configuration of metamaterial guarantees self-shielding, i.e., the metamaterial unit cells shield each other from the tissue. This further guarantees a negligible effect on resonance frequency. Also, any quality factor degradation due to proximity to the lossy tissue is compensated by the lens’s effect on the metamaterial, leading to improvement in the coupling coefficient, which defines the overall efficiency of the WPT system. The expected findings introduce new techniques to the international community that will benefit biomedical research.

３．研究の方法

A typical inductive WPT system for biomedical applications is bulky, as shown in Fig. 2(a). Both transmitter and receiver may suffer from tissue proximity, leading to two undesired effects: (i) Resonance shift and (ii) Quality factor degradation. This proposal analyzes the reasons behind these effects for the first time, and solutions are provided to overcome them. As shown in Fig. 2(b), a practical inductor consists of an ideal inductor and a parasitic capacitance. Therefore, the effective inductance can be modeled as a short circuit stub with a characteristic impedance, $Z_0 = \sqrt{\mu/\varepsilon}$, a phase shift constant $\beta = \omega\sqrt{\mu\varepsilon}$, and an l is the overall length of the inductor. The

[1. Research Objectives, Research Method, etc. (continued from the previous page)]
effective inductance (L_{eff}) can be calculated as (1), which is dependent on both the permeability (μ), and the permittivity (ε Correspondingly, since the tissue has a large dielectric constant, the effective inductance increases, and the self-resonance decreases due to the sensitivity to dielectric loading). Hence, resonance shift occurs, and the quality factor degrades.

$L_{eff} = \frac{Z_0 \times \tan\beta l}{\omega}$ $= \frac{\sqrt{\mu/\varepsilon} \times \tan\omega\sqrt{\mu\varepsilon}l}{\omega}$		➔	**The parasitic capacitive effect appears as a decrease in characteristic impedance (Z_0) and increase in electrical length (βl)**		(1)
For small βl ➔	$\tan\beta l = \beta l$ ➔	$L_{eff} \cong \frac{\sqrt{\mu/\varepsilon} \times \omega\sqrt{\mu\varepsilon}l}{\omega}$	➔	$L_{eff} \cong \mu l$	(2)

A design methodology will be proposed to overcome this problem. In the case of a small inductor length, equation (1) can be rewritten as (2). Hence, satisfying the condition $\tan\beta l = \beta l$ leads to an inductor independent of the tissue dielectric properties. For further illustration, proof of electromagnetic simulation is provided. An inductor sized 3 mm × 3 mm with a different number of turns is simulated in air and tissue environments. A comparison between the effective inductance is shown in Fig. 3(a) on the next page. Clearly, for a small number of turns (short-length inductor), inductance is not affected by the dielectric property of tissues.

Moreover, the simulated quality factors in air and tissue mediums are compared in Fig. 3(b) on the next page. The quality factor is degraded even if a short-length inductor is used because of the increased radiation ($\propto [\varepsilon_{eff}/\lambda_0]^4$), i.e. near the tissue, radiation resistance is amplified by a factor of ε_{eff}^4. Where, ε_{eff} and λ_0 are effective dielectric constant at the tissue/air interface and free-space wavelength, respectively. The Q-factor degradation appears to be an intrinsic property of the tissue and cannot be solved using conventional inductors. Instead, we propose using a new metamaterial, which we name a stacked metamaterial, to focus the magnetic field towards the receiver. The coupled quality factor (kQ-product) defines a WPT system performance. Hence, by improving the coupling coefficient (k), the overall kQ-product can be improved.

As described on the previous page, the proposed metamaterial is rigid against the resonance shift issue as its cells use short-length inductors. Furthermore, the proposed metamaterial structure is compared with the conventional metamaterial. The proposed metamaterial structure has two advantages over the conventional one for the target implanted IoT sensor applications. Besides the lens's effect of the metamaterials, the proposed metamaterial has a larger lateral size (d2>d1). Hence, the coupling between the metamaterial cells and the receiver is expected to be larger. In conventional metamaterial, all cells interface with the tissue, and a low-quality factor is expected. Instead, in the proposed metamaterial, cells are stacked above each other, i.e. only one cell interacts with tissues. Hence, the other unit cells are shielded and operate with a higher Q-factor. The proposed stacked metamaterial-based WPT system will be compact (more than 40% reduction in size).

４．研究成果

Ａ compact wireless power transfer (WPT) system with a novel metamaterial that enhances power transfer efficiency through human tissue was developed. Its design methodology was first

[1. Research Objectives, Research Method, etc. (continued from the previous page)]
proposed and verified by comparing it with the experimental results in a phantom. The developed WPT system achieved an AC-to-DC efficiency of over 35% with a 7mm x 7mm receiver.

A low magnetic loss metamaterial for a compact single-band WPT system and a robust wideband metamaterial for a dual-band WPT system were also proposed and verified through the experiment. Integrating these metamaterials in a compact WPT system resulted in significant improvements in power transfer distance and misalignment tolerance.

These innovations can potentially revolutionize the healthcare industry by enabling wireless charging of medical implants such as pacemakers and artificial hearts, improving patient comfort and saving lives.

5．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　3件）

1．著者名	4．巻
Aboualalaa Mohamed、Mansour Islam、Pokharel Ramesh K.	21
2．論文標題	5．発行年
Experimental Study of Effectiveness of Metasurface for Efficiency and Misalignment Enhancement of Near-Field WPT System	2022年
3．雑誌名	6．最初と最後の頁
IEEE Antennas and Wireless Propagation Letters	2010～2014
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1109/LAWP.2022.3188297	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

1．著者名	4．巻
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Hybrid SRR-based Stacked Metamaterial for Miniaturized Dual-band Wireless Power Transfer System	2023年
3．雑誌名	6．最初と最後の頁
IEEE Transactions on Antennas and Propagation	1～1
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1109/TAP.2023.3262977	有
オープンアクセス	国際共著
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1．著者名	4．巻
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2．論文標題	5．発行年
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3．雑誌名	6．最初と最後の頁
IEEE Transactions on Circuits and Systems II: Express Briefs	869～873
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10.1109/TCSII.2021.3123954	有
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1．著者名	4．巻
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2．論文標題	5．発行年
A multimode metamaterial for a compact and robust dualband wireless power transfer system	2021年
3．雑誌名	6．最初と最後の頁
Scientific Reports	(2021) 11:19941
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1038/s41598-021-01677-6	有
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2．論文標題 Analysis and design of diode physical limit bandwidth efficient rectification circuit for maximum flat efficiency, wide impedance, and efficiency bandwidths	5．発行年 2021年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-021-99405-7	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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1．発表者名 R. K. Pokharel
2．発表標題 MetaTx-introduction of metamaterial-assisted WPT system for biomedical implants
3．学会等名 Asian Wireless Power Transfer Conference (AWPT)（招待講演）（国際学会）
4．発表年 2022年

1．発表者名 Mohamed Aboualalaa and Ramesh Pokharel
2．発表標題 Extended Embedded Depth Using Cascaded Resonators Near-field WPT System with High Efficiency for Biomedical Implants
3．学会等名 2023 IEEE International Microwave Symposium (IMS)（国際学会）
4．発表年 2023年

1．発表者名 Alshhawy Shimaa、Barakat Adel、Yoshitomi Kuniaki、Pokharel Ramesh K.
2．発表標題 Low Magnetic Loss Metamaterial Based Miniaturized WPT System for Biomedical Implants
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4．発表年 2022年

１．発表者名 Jiang Xin、Pokharel Ramesh K.、Barakat Adel、Yoshitomi Kuniaki
２．発表標題 Wideband Stacked Metamaterial for a Compact and Efficient Dual-band Wireless Power Transfer
３．学会等名 2022 IEEE International Microwave Symposium (IMS)（国際学会）
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関