Low-Loss Wireless Implant Telemetry Using Magnetoinductive Waveguides

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***Abstract*—We introduce a novel wireless implant telemetry system that utilizes magnetoinductive waveguides (MIW) to break state-of-the-art boundaries in terms of: (a) transmission loss, and (b) bandwidth. Magnetoinductive waveguides rely on the careful design of a series of resonant loops, where excited current on the transmit loop leads to the current propagating as magnetoinductive waves to the receive loop. A MedRadio (401-406 MHz) MIW is shown to communicate with a 49.3 mm^3 implant at 1 cm depth with a transmission loss of only 19.4 dB and a bandwidth of 187.4 MHz. This represents an improvement of over 30 dB and 85 MHz over a similar Radio-Frequency (RF) based system. Notably, the reported MIW framework empowers a full wearable system that can be integrated into clothing to handle wireless nodes placed both on and inside the human body.**

***Index Terms*—Electrically small resonant loops, magnetoinductive waveguide (MIW), magnetoinductive waves (MI waves), wireless body area networks (WBANs), implant telemetry.**

I. Introduction

WIRELESS IMPLANTS are vital to improving patient outcomes and well-being. Implants can be used for diagnostic purposes, therapeutic purposes, and for patient assistance [1]. With the wide range of applications, issues barring the expansion of wireless implants entail: high transmission loss associated with the lossy biological tissue environment; need for wide bandwidth to avoid detrimental detunings and empower high data rates; low power requirements for transmission due to the long implant lifecycle; and integration into the existing user wireless body area network (WBAN) [1]. Three technologies have been primarily explored for implant communication: radio frequency (RF), galvanic coupling, and magnetic induction. RF systems suffer from loss present in human tissue to RF waves, and must handle the complexity of antenna miniaturization while maintaining performance [1]. Galvanic coupling must also deal with the loss of human tissue and does not easily integrate into existing WBANs [1]. Magnetic induction suffers from low bandwidth with transmission power falling rapidly with increasing distance [1].

To mitigate these issues, we introduce the magnetoinductive waveguide (MIW) as a new method of implant telemetry that overcomes limitations in the state-of-the-art. MIWs operate through exciting a current onto the transmit loop, which in turn induces a current onto the neighboring loops. Through careful design, the current propagates to the receive loop as a magnetoinductive wave. Our previous work on wearable MIWs has shown improvements versus the above technologies for on body applications and has also demonstrated invariance to human tissue properties [2], [3]. The latter indicates potential for significant improvement in implant telemetry versus the state-of-the-art. Here, it is the first time that we explore MIWs within the context of wireless implants. Given the improvement in body-worn applications, MIWs further allow for seamless integration of implants into the existing WBAN framework.

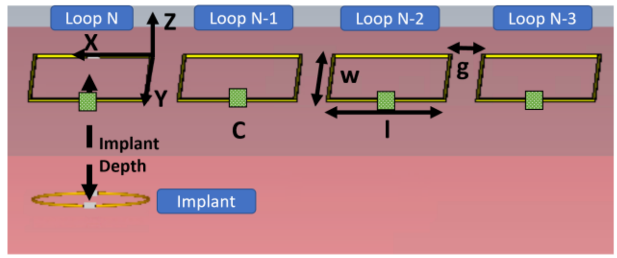

Fig. 1. Generic setup of the MIW implant system (perspective view).

II. MIW System Overview

As a proof-of-concept, we construct an MIW centered in the MedRadio band of 401-406 MHz [4]. This frequency is in no way limiting to our approach. To mimic human tissue, the MIW is placed on a 20 cm × 10 cm × 10 cm block with electrical parameters equal to 2/3rds that of muscle to approximate human tissue. Per Fig. 1, the MIW is formed using 11 loops where $l = 1\ cm, w = 3.48\ cm$, and $g = 0.25\ cm$. A capacitor of $C = 2.1\ pF$ is also added on each loop to make them resonant. The implant is chosen to be a circular loop with 5 mm radius, made resonant at 403 MHz inside the human tissue with a 4.7 pF capacitor. It is placed 1 cm below the surface of the tissue and placed in the center of the receiving loop unless otherwise stated.

III. Performance Analysis

A. Transmission Loss and Bandwidth Performance

Before implementing the implant, the MIW has a minimum loss of 9.8 dB, a 10 dB bandwidth of 37.6 MHz, and a center frequency of 403 MHz. With the implant introduced into the system, the minimum loss remains 9.8 dB and the bandwidth increases to 38 MHz while the center frequency remains unchanged. The transmission between the implant and

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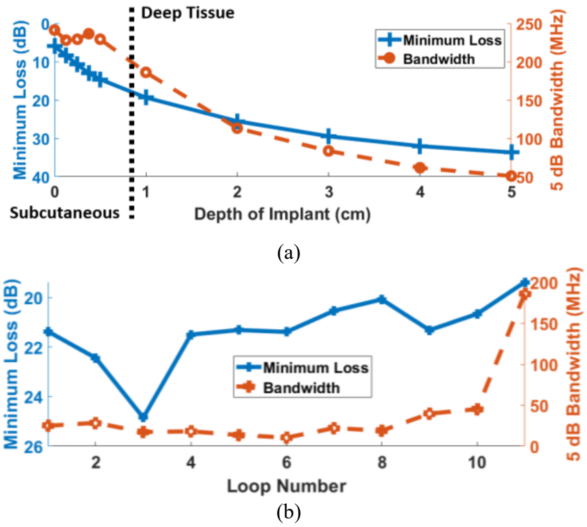

Fig. 2. Implant-body worn node transmission performance for (a) increasing depth of implant and (b) across the MIW.

TABLE I
MINIMUM LOSS PERFORMANCE VS RF-BASED SYSTEMS

Ref	Implant Depth	Transmission Loss
[6]	4 mm	34 dB
This work		14 dB
[7]	9 mm	24 dB
This work		19 dB
[5]	1 cm	50 dB
This work		19 dB
[8]	5 cm	81 dB
This work		34 dB

the receive loop has a minimum loss of 19.4 dB and a 5 dB bandwidth of 187.4 MHz. We use 5 dB bandwidth here instead of 10 dB bandwidth due to the flat behavior of the transmission coefficient. This is an improvement of over 30 dB and 85 MHz versus an RF-based system operating at the same frequency [5].

B. Implant Depth

Wireless implants can be placed at a variety of different depths depending on the application. Particularly of interest are two categories of implants which we classify as subcutaneous (0 to 5 mm) and deep tissue (1 to 5 cm) implants. Fig. 2(a) shows the minimum loss and bandwidth performance of the implant and receive loop at changing implant depth. As expected, the minimum loss monotonically increases with increasing depth. This is due to the distance dependence of induction. The bandwidth in the subcutaneous range fluctuates around 225 MHz. Once in the deep tissue range, the bandwidth monotonically increases as well. For subcutaneous depths, the minimum loss remains above 14.6 dB and the bandwidth remains above 228 MHz. The minimum loss at 5 cm reduces to 33.7 dB and the bandwidth decreases to 50.8 MHz. This system outperforms several RF based systems as referenced in Table I.

C. Propagation over the MIW

One of the main benefits to utilizing a wearable MIW structure for implant telemetry is the ability to couple the implant with any of the loops in the MIW to maintain transmission to the final receive loop. In Fig. 2(b), we examine the changing transmission performance as the implant is aligned with each of the loops in the MIW at a depth of 1 cm. For all loops but the receive loop, the bandwidth is limited by the MIW performance. This is not the case when the implant is coupled to the receive loop because this transmission only relies on magnetic induction and not magnetoinductive waves. This explains the large decrease in bandwidth as the implant is placed elsewhere along the MIW. For all loops, barring the transmit loop, the minimum loss stays within the range of 24.9 dB and 20.1 dB and the bandwidth stays within the range of 10.4 MHz and 45.2 MHz.

The MIW system outperforms current state-of-the-art RF based systems in terms of minimum loss at many depths ranging from 4 mm to 5 cm. In addition to this performance, the implant may be placed under any loop in the MIW and still maintain the improved minimum loss performance. This allows for increased ease of use by removing the need for precise alignment.

IV. CONCLUSION

In this work, we introduced an MIW-based solution for implant telemetry and simultaneous communication between body-worn wireless nodes. When the implant is at a 1 cm depth and aligned ideally, this system has a minimum loss and 5 dB bandwidth of 19.4 dB and 187.4 MHz, respectively, while maintaining near ideal performance for body worn node-body worn node communication. This MIW configuration significantly outperforms state-of-the-art systems while improving upon the seamlessness and ease of use of implant telemetry via a low profile, wearable design.

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