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A Review on Design, Analysis, and Application of Conformal Antennas for Capsule Endoscope

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***Abstract*—For human healthcare applications, radio frequency sensors that can be used inside the body are developing day by day. In this kind of sensor, an implantable antenna in a capsule endoscopy system is executed leading to communication with external equipment. For this case, these implantable circuits are growing famous in the biotelemetry field for which large bandwidth, and high gain, with compact configurations, are required in the lossy human tissue. This work presents the various state-of-the-art conformal antennas for capsule endoscopes, with a focus on introducing structures and outcomes achieved from the simulation/measurement process. As this paper is reporting the recent developments in the domain of capsule endoscopy, anyone reading this work will get general and up-to-date views regarding this concept.**

***Index Terms*—Antenna, biomedical, conformal, capsule endoscope, industrial, scientific, and medical (ISM) band.**

I. INTRODUCTION

Biomedical devices can be utilized for various applications like sensing, monitoring, and drug delivery to patients under the diagnostic and therapeutic functions [1], [2]. One of the main parts to be used in biotelemetry applications is antenna configurations that can be operated at the medical implant communication service (MICS) band (402–405 MHz), the industrial, scientific, and medical (ISM) bands (433.1–434.8 MHz and 2400–2483.5 MHz), and also midfield band (1520–1693 MHz) [3]–[5].

Wireless capsule endoscopy, since 1990s, provides a new treatment solution for diagnosing various diseases and overcoming the pains [7]–[9]. In these systems, the existence of an antenna is essential since it transmits the collected information from inside the body to the receiver outside of the body. Among various antennas, the flexible conformal capsule antenna has become famous nowadays due to its miniaturization and practical verification [10]–[12] operating at 915 MHz (0.5–5.0 GHz). Also, engineers are paying attention to the ingestible capsule endoscopy systems as well leading to receiving images of the inside body parts. These types of antennas are used by sick alive humans/animals and the included camera captures images of the inside organs [13]–[15]. So, the main target of these wireless capsule endoscope systems along with the used antenna is to monitor and cure diseases with the help of measuring physiological signals at a certain distance [16]–[18]. In designing and simulating capsule

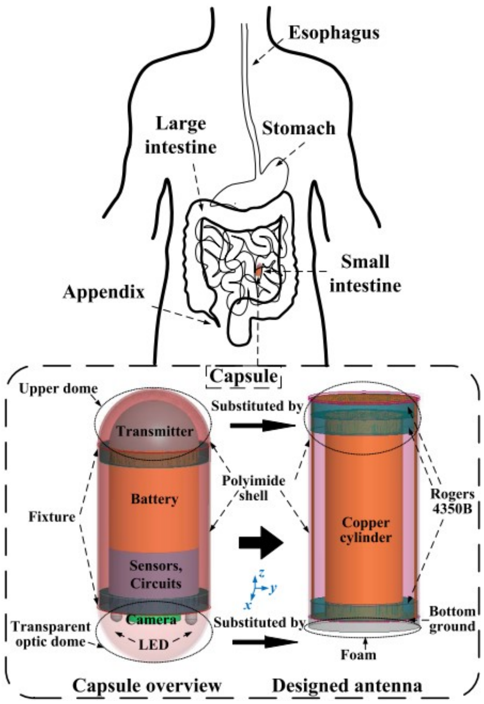


Fig. 1. A general view of wireless capsule endoscopy system presented in [6].

antennas, it is important to pay attention to all used electronic and optical components. As Fig. 1 shows, these wireless-based devices include a battery, a biocompatible shell, an optical dome, a light-emitting diode, a camera, transmitter circuits with antenna(s) in which the antennas have the duty of transmitting data to the outside body devices [19]. For analogous purposes, the authors in [20] have discussed ultra-wideband antennas for a wireless capsule endoscopy system. Hence, miniaturization technologies, enhanced bandwidth methods, polarization modes, and different antenna types have been widely described.

Due to the importance of the capsule endoscope subject in biomedical applications recently, in this work we report a comprehensive summary regarding the designs, simulation/measurement results, and applications of presented circuits in this content. Hence, any designer by referring to this study will get the general view in a fast way. The remainder of this work is as follows: Sec. II summarizes the various designs, and outcomes that have been published in the very recent years in the domain of capsule endoscope. And as the last section, Sec.III concludes this paper.

II. CAPSULE ENDOSCOPE SYSTEMS AND THEIR APPLICATIONS

In the configuration of wireless communication systems for implantable biomedical devices, presenting high-performance antennas have been generated. Various studies address the requirements of a capsule endoscopy antenna such as compact and low power to improve communication lifetime and wide bandwidth and high gain for effective data transmission. Figure 2 illustrates the composition of a wireless capsule endoscopy system.

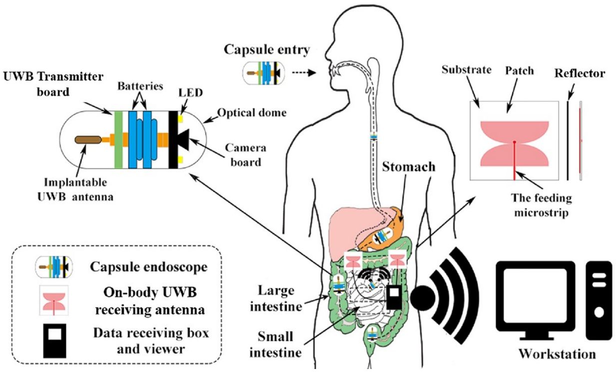


Fig. 2. Composition of a wireless capsule endoscopy system presented in [20].

In this case, various antennas for telemetry applications have been designed, analyzed, and employed, over the past decades. This section is devoted to describing various structures of conformal antenna for capsule endoscopes, and then the related outcomes of each one are explained. Also, the application of each presented literature is considered.

A planar switching integrated quadrant coil antenna is presented in [21] for reducing the lateral and angular misalignment drawbacks. This presented antenna can be employed for medical implants, wireless endoscopy capsules, and also wearable devices. The overall configuration is optimized by field-forming methodology to construct switched orthogonal H-field components. In [3], a multiband spiral-shaped implantable antenna is presented which includes a flat-type scalp implantable device and also a capsule-type leadless pacemaker. The overall size of the structure is 7 mm × 6.5 mm × 0.377 mm with the maximum gain values of -30.5, -30, -22.6, and -18.2 dBi at 402, 433, 1600, and 2450 MHz, respectively. This implantable antenna demonstrates that it can be used for telemetric applications. In another study, [10], a conformal antenna with a total size of 30.5 mm × 4.6 mm × 0.05 mm that results in a maximum gain of -21.5 dBi at 915 MHz is presented. Additionally, it includes a 4.5 GHz ultra-wideband impedance matching bandwidth that covers the required frequency band in an effective way. A circularly polarized (CP) omnidirectional radiation antenna that can be used for wireless capsule endoscope is presented in [22] which is working at a bandwidth of 0.902–0.928 GHz. The presented antenna is placed in the center of a cylindrical homogeneous muscle tissue during the simulation and the CP radiation covers a range of θ=49°–144° which is a successful wide domain in the elevation plane. The presented capsule endoscopy antenna in [23] is operating at ultra-wideband (UWB) frequencies and the general structure of this antenna is depicted in Fig. 3. This configuration involves a total size of 8.4 mm × 6 mm × 1.036 mm and it is implemented on the Rogers1 RT Duroid 6100 (tm) substrate.

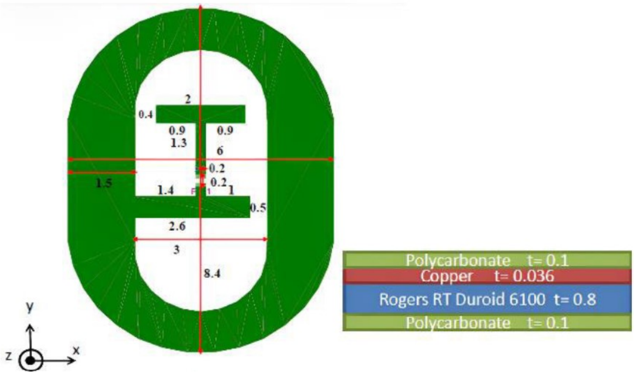


Fig. 3. Capsule endoscopy antenna presented in [23]; a) top view and b) side view; All dimensions are in mm.

In [24], a Multiple-Input– Multiple-Output (MIMO) implantable antenna system which involves capsule endoscopy is designed, fabricated, and measured. The used substrate is RO3010 and the operated fractional bandwidth is 33.9% covering MICS and ISM bands with the maximum realized gain of -30 dBi. Also in [25], a four-antenna module is presented for capsule endoscopy MIMO operation in which the maximum gain of -18.1 dBi is measured. This structure can be used for transmitting high-resolution images in medical applications. In another study as [26], the MIMO structure is presented that covers the frequency band from 0.61 to 1.51 GHz that is positioned in the upper and lower sections of the capsule. Another structure for the CP capsule antenna is presented in [27] that is an asymmetric U-shaped strip and a protruding L-shaped stub printed on the top of the dielectric substrate. Based on the various simulations that are executed for this antenna, it is observed that the impedance bandwidth is insensitive to human tissues. Figure 4 shows the general structure of the presented dipole antenna inside the capsule with the capsule shell that is developed in [28]. For simulating this configuration, channel characteristics are evaluated both in frequency and time domains. Additionally, the model is substituted inside various areas of the small intestine of the voxel models existing in the CST tool.

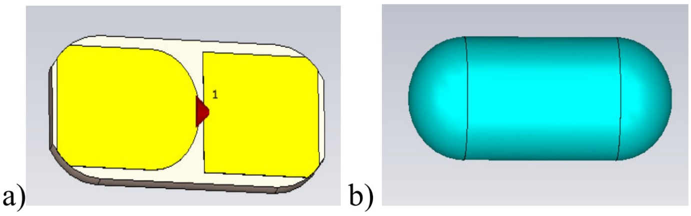


Fig. 4. Dipole antenna structure presented in [28]; a) inside view and b) capsule shell.

In another study, [29], a differentially fed capsule antenna along with a complex input impedance is presented in which the main configuration is a circular flat shape. For this structure, the gain and efficiency of -27.9 dBi and -31.9 dB are obtained in the case of locating the antenna inside a simplified muscle phantom. A dual-circular-polarized conformal loop antenna with the size of 32 mm × 10 mm × 0.0257 mm is presented in [30]. The antenna is fabricated and the measurement results reveal impedance bandwidths and gains at 402 MHz, 915 MHz, and 2.4 GHz are 236.2%, 104%, 55.4%, and -29.71, -28.7, and -20.8 dBi, respectively. Another compact MIMO implantable antenna is presented in [31] with a peak realized gain of -20.5 dBi and can be operated at a power level of 3.97 mW. The size of the antenna is 5.35 mm × 6.2 mm × 0.12 mm and the meandered resonators and slots are employed in the ground plane. Another capsule endoscope with a symmetrical closed-loop conformal antenna is designed in [32] working at 608–614 MHz and also ISM band frequencies. The operating input power for this antenna is 2.42 mW. A weighted centroid localization algorithm is first presented in [33] for obtaining high-accuracy localization through only a sparse reception matrix. Afterward, a wearable localization system for wireless capsule endoscopy is depicted. For increasing the data rate communication for inside and outside the body, ultra-wideband communication issue is provided in [34]. For this case, a channel modeling technique based on a plane wave propagating with the help of a multi-layered dielectric is presented. Additionally, the optimum position of multiple receive antennas on the abdominal surface with the help of this approach can be determined. Fig. 5 presents the human voxel body model for a transmitter-receiver pair in which Tx is the transmitter location inside the gastrointestinal tract, and Rx is the receive antenna location on the body surface. Here, the power is transmitted just only in the direction of the receiver (not in other directions). Hence, the transmitter knows in which direction the receiver is settled.

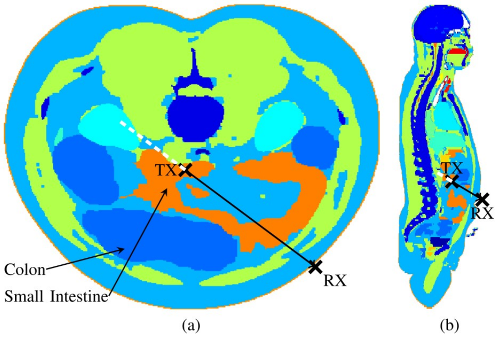


Fig. 5. View of one slice from; a) top and b) right side presented in [34].

In [35], a compact-size transparent thin-film dual-polarized antenna has been designed to provide a 360-degree broadsight view of the wireless capsule endoscopy system at 2.45 GHz. Besides its physical-structural advantage for the targeted application, the antenna has -26.3 dBi gain and 855 MHz bandwidth. In addition, dual-polarized design can provide benefits such as reducing cross-polarization interference, saving equipment space, and improving fading resistance and signal quality. Figure 6 shows the measurement schematic and a practical experimental setup for the presented transparent thin film antenna. The radiation pattern of the proposed antenna and a conventional copper-based antenna has been given for comparison.

The on-body wideband dual-polarized antenna is presented in [36] for improving the link performance of wireless capsule endoscopy systems which operate from 381 to 990 MHz. In a depth of 60 mm inside of the body, a peak $\mid S_{21} \mid$ of -25.5 dB is observed. The presented antenna is able to work with a receiver system properly due to its enhanced transmission performance. In another study, [37], CMOS integrated multiplexed fluorescence bio-molecular sensor arrays are presented that are designed with 65 nm technology. This design provides a solution and eases the real-time measurement of complex bio-molecular processes. In [38], a compact dual-element capsule endoscopic MIMO antenna operating at ISM band is presented. This type of antenna has a total size of 9.01 mm^3 , and a gain of -24.6 dBiC with an isolation level of 29.7 dB in the whole bandwidth. Other implant capsules are presented in [39] that without any need for any active transmitter, the devices can communicate with an on-body device. The measurement results show that the maximum channel loss variation of 35 dBV is recognized in the received signal. The presented main configuration of this study is based on the one-way backscatter communication based on conductive coupling. The miniature antennas that can be involved in ingestible capsules are studied in [40]. The general structure of the presented antenna is depicted in Fig. 7 in which the center frequency is 433 MHz. As it is clear from this figure, the antenna configuration is rolled into cylinders with a target of reflecting inside a capsule.

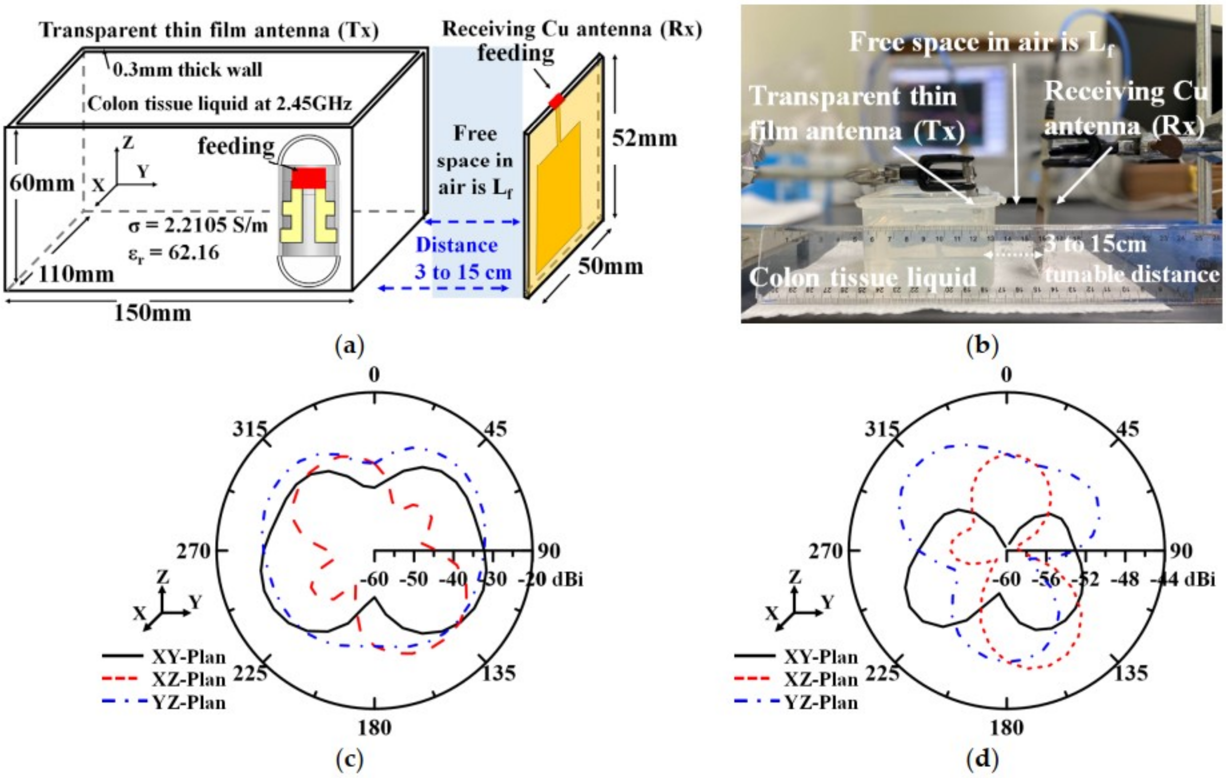
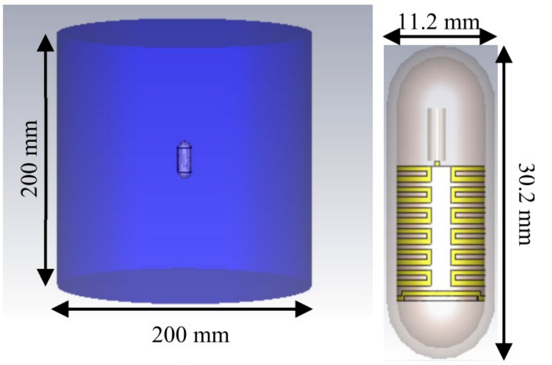


Fig. 6. (a) Measurement schematic, (b) experimental setup (c) radiation pattern for the proposed antenna, and (d) radiation pattern of the conventional copper-based antenna presented in [35].



(a) (b)

Fig. 7. Simulated capsule presented in [40]; a) capsule in surrounding b) detail configuration of antenna.

An antenna operating at 915 MHz ISM band for robust communication that is with quasi-isotropic radiation pattern is presented in [41]. The configuration of this type of antenna is integrated with dummy electronics that are encapsulated in a copper cylindrical bucket. In the simulation, this antenna has a gain variation of around 8 dB and the peak gain is -20.7 dBi. The wireless capsule endoscopy can also be used for animal husbandry as well. In [42], an ingestible capsule MIMO antenna is designed, simulated, and measured that is bent into a cylindrical profile with U-slotted strips. The presented structure is able to mimic a real-time pill camera and the operational bandwidths are both in 2.45 GHz and also 3.1–10.6 GHz frequencies. The device is implanted in the skin of animals the related radiation characteristics are considered with respect to the received data. Figure 8 presents the general structure of the presented antenna in [43]. This antenna is working at the operational band frequency of 3.75-4.25 GHz by paying attention to the IEEE 802.15.6 standard. The depicted antenna has an overall size of 89 mm × 60 mm × 21 mm with a measured gain of 8 dBi at center frequency and it is suitable for both male and female patients. The important point that can be taken from this literature is to evaluate the antenna matching in both 'abdomen area' and 'back area' of human bodies as shown in Fig. 9.

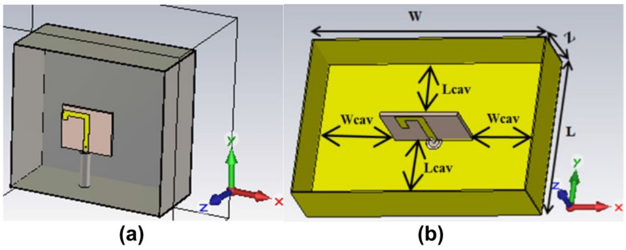
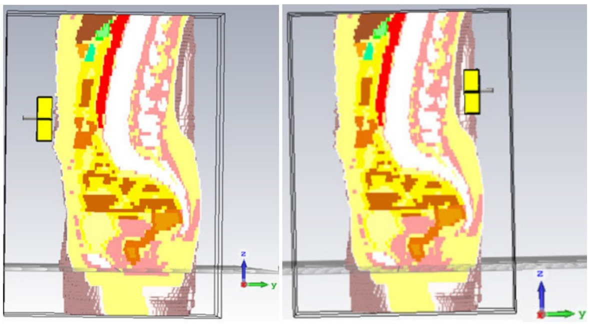


Fig. 8. a) Floated view b) grounded view of presented antenna in [43].

Another work presented for the wireless capsule endoscopy



(a) (b)

Fig. 9. The voxel mode presented in [43] a) abdomen area, and b) back area.

system at 2.45 GHz is the circularly polarized antenna design with the 120 MHz bandwidth given in [44]. In this work, the method used to achieve circular polarization and to reduce the size is explained. The picture of the prototype of the antenna and the measurement setup are shown in Fig. 10. The simulated specific absorption rate (SAR) distribution in the skin model (1g) at 2.45 GHz is given in Fig. 11. The maximum SAR value of the antenna in the small intestine is 216 W/Kg, the maximum SAR value of the antenna in the large intestine is 176 W/Kg and the maximum SAR value of the antenna in the stomach is 168 W/Kg shown in the dashed box.

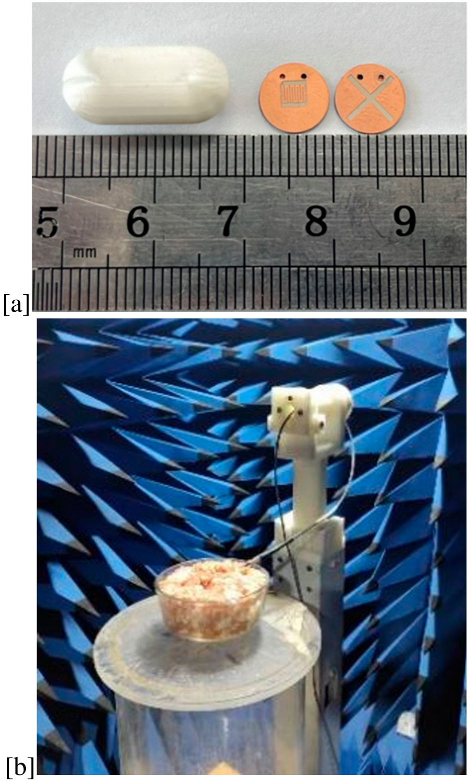


Fig. 10. (a) The proposed antenna prototype, and (b) measurement setup presented in [44].

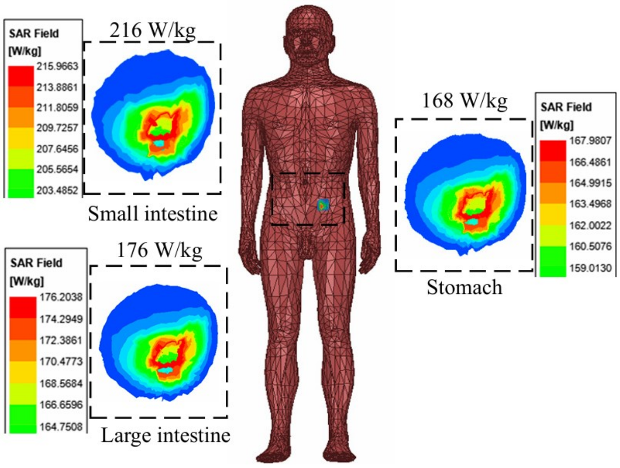


Fig. 11. The simulated SAR results at the designed frequency range presented in [44].

III. CONCLUSION

Implantable and ingestible devices can monitor and diagnose various diseases even in the case of mobility of patients. These wireless devices operate inside the body and transmit data to a receiver outside the body. As previously discussed, the most important part of these devices are antennas that must be operated in a complex human body environment. Hence, providing sufficient gain and also maintaining reliable communications are some of the important specifications that each biomedical antenna must satisfy. This paper is devoted to making a summary of the very recently published papers on the concept of capsule endoscopes which introduce the configured structures, analysis, and various outcomes achieved from the presented designs. This work will facilitate the research step of engineers planning to work on the conformal and implantable antennas.

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