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Analysis of an ultra miniature capsule antenna for gastrointestinal endoscopy

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ABSTRACT

An efficient miniaturized antenna used in Wireless Capsule Endoscopy is presented. Wireless Capsule Endoscopy is the best option to replace conventional Endoscopic methods. An antenna in this capsule provides definitive electromagnetic performance of the system which is used for inspection of the gastrointestinal tract (GI). The proposed antenna has a Double C-shaped Resonant Structure (DCRS) embedded with the antenna structure. This structure can introduce a strong electric response over any desired frequency and thus metamaterials with negative permittivity can be constructed. The parameters of the metamaterial are extracted to confirm its artificial behavior. The characterization of the miniature antenna is done at 2.45 GHz using coaxial cables and we obtained a simulated gain of −23 dBi and the achieved fractional bandwidth is 20.4%. This paper also explains the method for the calculation of the impedance of the isolated antenna structure without any conventional coaxial cable. This antenna design is well suited for ingestible applications as it is miniaturized and operates in the ISM band.

1. Introduction

Wireless implantable and ingestible devices in biology and medicine has facilitated various diagnostic and therapeutic methods. Traditional endoscopic tube through throat in turn induces pain and discomfort to the patients. In this scenario, the painless wireless ingestible capsule system occurred as a perfect alternative to the conventional method. But lot of factors affect this system performance which includes size, gain, impedance bandwidth, detuning effects, sensitivity to the surrounding environment, radiation safety and polarization shift. Among these, miniaturization of the antenna is one of the greatest requirements for wireless ingestible devices [1,2]. A good compromise between the characteristics of the antenna such as volume, bandwidth and efficiency is an important aspect of the antenna miniaturization. This will severely affect the antenna characterization, including bandwidth, efficiency, gain, polarization purity and also the position of the feed given to the antenna [1].

Miniaturization of an antenna can be achieved by using high permittivity substrates or by using radiating elements of small sizes. It also depends on the conducting plane size. The size of the radiating element can be reduced by creating slots over it [2]. One of the major challenges and advances related to the miniaturization of ingestible antenna is to determine how to characterize it without disturbing its behavior [3,34]. Impedance matching is an important design criterion in an ingestible antenna design as the capsule system has other electronic components associated with it. Matching in an antenna can be done by using coaxial cables by correctly positioning it over the radiating element of the antenna structure. But for ingestible antennas which are having a small sized ground plane, characterization using coaxial cables results in a variation of their behavior [4]. The impedance and radiation characteristics of the miniature antennas will be disturbed when the RF cable is placed in the reactive field region of the antenna, since this modifies the near field and the current distribution of the antenna. Both the real and reactive parts of the input impedance will be modified through this action. The cable will act as a radiator when there is a leakage of current from the chaises to the outer surface of the cable caused when the antenna and the chaises are not properly balanced [5].

Use of ferrite chokes on the outer wall of the cable, use of a quarter wavelength sleeve and dual band Baluns are certain techniques used to overcome the effects of the cable [6]. One of the ways to suppress the stray current produced at the outer conductor of the coaxial cable is to connect the antenna through a balun to the unbalanced coaxial cable. Through this the coupling and errors will be reduced and thus the antenna can be measured accurately. The antenna plus the ground plane assembly will be transformed into a variable balanced antenna that is in between a balanced

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and an unbalanced condition by the effect of the ground plane and also by the presence of a conducting human body with different postures since the ingestible antenna rolls over the digestive tract when the capsule is swallowed by the patient. Normally baluns are used to connect balanced loads to unbalanced loads. In the case of the varying balanced condition the suitable design to overcome the parasitic current is a sleeve balun or a bazooka balun [7]. The sleeve balun will create an open circuit to reduce the stray current on the coaxial cable. Thus, with an introduction of a sleeve balun the cable used for the calculation will no longer disturb the characteristics of the antenna assembly. The baluns are normally used to suppress the odd mode cable current on the coaxial cable and the metal wire structure [8]. The quarter wave length sleeves are effective over the frequency range of 400 MHz to 1 GHz.

The reduction of RF cable effect by the use of the shorted sleeve baluns is band limited. For multi band operation there is a need to attach several narrowband baluns for each frequency band [9,10]. The dual band balun is thus able to reduce the perturbations at dual bands. In addition to these cable effects, there is also a difference between results obtained by measuring the antenna with the results obtained during simulation. This is due to the fact that we are using an infinite length cable during measurement and a finite length cable during the simulation and the characteristics of the antenna will vary with the cable length. This effect can be corrected by simulating an infinite cable which is achieved by using an absorbing boundary condition at the cable extremity [2]. Thus we can extract the properties of the isolated antenna without the cable from the antenna under test, if we know the simulation results of the single antenna and the antenna with infinite length cable. In case of a monopolar wire patch antenna, by the simulated results of the single antenna and the antenna with the "infinite" coaxial cable structure a transfer function can be created for any given cable configuration as Eq. (1) [2].

$$H_{imp}(f) = \frac{Z_{ca}(f)}{Z_a(f)} \tag{1}$$

Where Z_{ca} (f) is the impedance of the antenna with infinite coaxial cable structure and Z_a (f) is the impedance of the single antenna structure obtained through simulation. Thus, if we know the value of this transfer function and the measured value of the impedance of the antenna structure we can easily retrieve the properties of the single antenna structure which is not affected by the RF cable effects.

The process of achieving miniaturization of an ingestible antenna by placing the radiator over a high dielectric substrate has got several drawbacks [11]. The electromagnetic fields will remain highly concentrated around the high permittivity region. Moreover the impedance matching is difficult, since the high permittivity medium has got low characteristic impedance. These limitations can be overcome by the use of metamaterials, which helps to boost the basic antenna features of impedance matching, bandwidth, efficiency and gain [12]. In this paper, we propose a Monopolar wire Patch Antenna loaded with Double C shaped Resonant Structure (DCSR) operating at 2.45 GHz medical band and analyse its impedance and miniaturization characteristics to validate the antenna for an ingestible capsule system. Compared with the traditional designs, DCR structure would reduce the antenna volume to great extent which is the main goal of an ingestible system [23–25].

2. Miniature antenna design

2.1. Monopolar wire patch antenna

A monopolar wire patch antenna can be designed to be operating at 2.45 GHz frequency with a maximum dimension of $\lambda_0/25$. A coaxial probe connected to the top hat through the ground plane and the dielectric substrate is used to feed the antenna. A low frequency resonance is obtained through the ground wire which acts as a short circuit to the antenna [13]. The capacitance of the antenna is represented by the top hat above the ground plane. The resonance frequency varies with the size of the top hat, the height of the antenna, the permittivity of the substrate and the ground wire diameter [14]. The antenna top hat is made up of a closed slot which is loaded by a discrete capacitor and thus the resonant frequency is further reduced to a lower value [15].The antenna is 5 mm × 5 mm × 2 mm in dimension with a dielectric substrate of permittivity 3.55. The monopolar wire patch antenna with a coaxial feed is shown in the Fig. 1. With a capacitor value of 0.66 of a return loss of −12 dB and an impedance of 73 Ohm is obtained at the operating frequency 2.43 GHz. The gain of the antenna is −23 dB. Monopolar wire patch antenna has bipolar like radiation characteristics [13].

But the antenna miniaturization and the losses due to the conventional coaxial cable used for measuring the properties of the antenna leads to poor efficiency over the operating frequency band [21]. Thus the techniques to improve the efficiency of the miniature antenna must be considered. The efficiency of the miniature antenna can be improved by incrementing the slot length over the radiating structure, by varying the properties of the material used as the substrate for the antenna and also by the use metamaterials. In this paper the introduction of metamaterials for efficiency improvement is taken into consideration.

2.2. DCR structure

The metamaterials are artificial structures whose electromagnetic responses are not available in the nature [16,17]. These metamaterials are constructed with negative permittivity and provides an alternative design approach for obtaining efficient electrically small antenna (EESA) systems [18,31]. A double C shaped resonant (DCR) structure is being embedded with the antenna structure. This structure can introduce a strong electric response over any desired frequency at the desired split with broad bandwidth [26–33]. Here planar DCR structure is examined for ingestible capsule applications. Moreover, such proposed DCR structure provides good miniaturization as it is evident from its dimensions. These results exhibit that our proposed antenna embedded with this DCR structure is well suitable for ingestible capsule system. The rectangular double C shaped resonator (DCR) structure is shown in the Fig. 2. [19]. The dimension of the rectangular substrate is 5 mm × 2 mm with a dielectric constant of 3.9. The

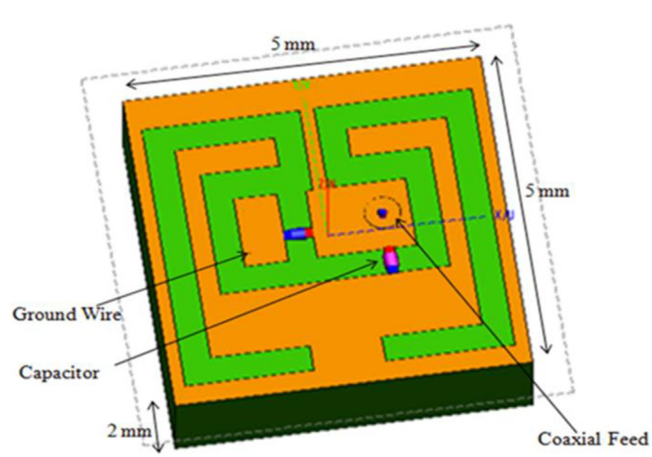

Fig. 1. Monopolar wire Patch Antenna.

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