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On-Chip Integrated Antenna Structures for Biomedical Implantable Sensors

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Abstract

This paper explores some different geometries of integrated antennas in a 0.35 µm CMOS technology for devices operating in the internationally available unlicensed 2.4 GHz band. At this frequency, the wavelength is short enough to implement small antennas with dimensions economically feasible for silicon integration.
Two are the considered different families of structures: spiral and dipole antennas, and some different antenna structures (single-loop, 4-loop, double-4-loop, dipole, bent-dipole, meander-dipole) are examined, all modeled and simulated in Ansoft HFSS. Their inductive and radiation characteristics are compared. Chip dimensions of the order of one square millimetre are considered.

Keywords: temperature sensor; on-chip antenna; wireless sensors; CMOS integrated sensors.

1. Introduction

Miniaturized integrated antennas are essential to the implementation of novel intelligent systems with no off-chip components for wireless communication. The on-chip antenna concept is the actual trend in integrated wireless sensor systems because it is a practical solution to compact, small size and low cost devices for short range applications, like RFID tags and biomedical sensor data transmitters. So an on-chip antenna represents a possible solution for a fully integrated wireless system, paving the way to new unexplored applications, such as miniaturized sensors. Rapid scaling of low cost CMOS technology has enabled circuits and systems to operate into the micro/millimeter wave frequency band, where the required antenna size shrinks and makes the implementation of an on-chip antenna feasible. And the feasibility of an on-chip antenna integration has been fully demonstrated only recently[1, 2] with a wide use of different interfaces and transmission standards and various antenna topologies.

This study originates from a previous work, in which, exploring the fully integrated wireless sensors field, a device with on-chip antenna for short range wearable biomedical applications was realized, with the aim of demonstrating the feasibility of such an antenna structure. A single-loop antenna was used in that case[3]. Simulations and characterizations show it is possible to obtain such a radiating element, so, with the aim of examining new antenna solutions for improving the performances of the transmitted signals, in this paper some different antenna structures

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have been considered, simulated and compared. The sources of losses have been also considered, affecting the radiation efficiency.

2. Integrated Antenna Design

All the radiating elements this work deals with, are modeled and simulated in Ansoft HFSS, at a frequency of 2.4 GHz, with the aim of obtaining their characteristic values. The stack-up refers to a 0.35 μm CMOS standard technology and consists of a 300 μm Si substrate ($\rho = 19\ \Omega\cdot$cm) and a thick top Al metal layer. A 4 μm oxide layer ($\rho = 10^{10}\ \Omega\cdot$cm) between the metal layer and the lossy Si substrate acts as insulation. The typical dimensions of the metal cross-section are 20 x 1 μm^2 and there is no ground plane in the bottom of the chip.

A loop antenna is the natural candidate to be integrated on chip, and it is the starting point of this study, basically because the active circuitry can be placed in the centre of the chip. For obtaining a resonating antenna, its linear dimensions must be comparable with one half of the carrier frequency. For the frequency values of the devices this work deals with, a well-tuned dipole antenna (a loop antenna can be treated as a dipole one) should have linear dimensions of the order of tenths of centimetres. However, the chip dimensions (chip size of the order of square millimeter are considered) limits in turn the antenna ones, so it is not possible granting the best resonating conditions in our case. Furthermore, two sources of losses should be considered: losses due to the metal conductivity, which can be however neglected, and losses in substrate volume. The introduction of the substrate, indeed, leads to a lowering of the antenna performances: its radiation efficiency can be degraded, depending on the electrical conductivity of the material it is made of[4].

Some different antenna structures performances have been examined, investigating the effects in their behavior induced by varying the geometric and technological parameters. The inductive and radiation characteristics were therefore calculated.

3. Results

As an example, the single loop antenna of Fig. 1a is considered: it can be modelled with a circuit composed by an inductance L and two resistances, R_{rad} and R_{loss}, as in Fig. 1b. The *radiation resistance* R_{rad} models the antenna radiating effect, whereas the *loss resistance* R_{loss} represents the losses due to heating. Assuming a constant current I flowing through the antenna, the total power in input is done by the sum of the radiating power P_{rad} and the dissipated power P_{loss}:

$$P_{tot} = P_{rad} + P_{loss} = I^2 R_{rad} + I^2 R_{loss}.$$

Eddy currents are induced in the substrate as an effect of the current flowing in the antenna, so the dissipated power increases. Comparing the simulations in vacuum and in presence of substrate, indeed, the value of R_{rad} remains substantially unaltered (about 0.16 Ω) but, more important, an increase in R_{loss} value is observed: it varies from 6.15 to 10.25 Ω with the introduction of the substrate.

The current induced in the substrate produces a field emitted by the substrate itself, in particular by its edges. In Fig. 1c this effect is shown for the single loop antenna. This contribution increases the total field emitted by the device, and influences the characteristics of the antenna, in particular produces an increment of the directivity. However, for far field conditions, this effect vanishes, and only the electric field emitted by the antenna is detected.

Considerations like these can be done regarding all the other antenna topologies involved in this work, a comparison among which has been conducted considering gain, radiation efficiency and input impedance after matching all the structures with the output impedance of the driving signal generator source. In these conditions the maximum power is transferred in each antenna, so the comparison can be possible. Electric field and radiated power values have been also calculated for the two different considered families of structures: spiral (single-loop, 4-loop, double-4-loop) and dipole (dipole, bent-dipole, meander-dipole) antennas. Simulations results obtained by Ansoft HFSS together with average linear dimensions are reported in Table 1.

The number of loops does not improve the performances, as could be seen examining a 4-loop structure, neither improvements are reached superposing two similar structures, with the aim of increasing the length of the antenna, obtaining a double-4-loop one. So the single-loop antenna shows the best behavior in its family, with a -50.9 dB gain and a 1.5% radiation efficiency. But the dipole set structures show better results. In particular, the bent-dipole shows a 7 dB gain, and a 1% radiation efficiency increase, with respect to the single-loop antenna. A simulation study aimed at highlighting the technological parameter tolerances effect on the antennas have shown that these effects are rather poor, namely of the order of 5% on the emitted electric field.

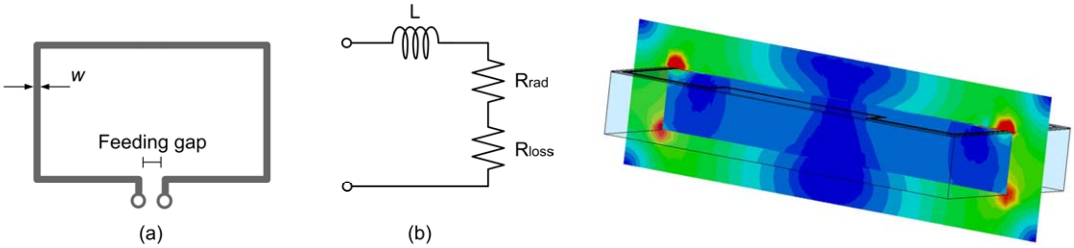
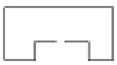
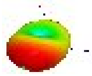
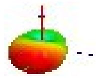
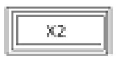
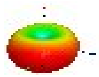
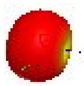
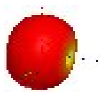
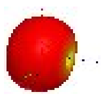


Fig. 1. (a) Single-loop antenna and (b) its equivalent circuit; (c) electric field evaluated with Ansoft HFSS on a plane crossing the chip in near field conditions.

Table 1. Simulations results for the various matched antennas topologies. Average linear dimensions and electromagnetic parameters are reported.

Antenna topologies	Emax [mV/m]	Gain [dB]	Umax [μWatt]	Radiation Efficiency [%]	Input impedance	Average length [mm]	Radiation pattern
	22,2	-50,9	0,60	1,50	11 + j 103	6	
	10,3	-57,5	0,14	0,35	128 - j 139	24	
	8,7	-58,9	0,10	0,24	21 + j 30	50	
	33,4	-47,3	1,50	1,16	689 - j 910	2	
	53,2	-43,3	3,80	2,70	489 - j 599	4	
	36,4	-46,5	1,80	1,40	589 - j 659	2,6	

4. Conclusion

Simulations have shown that the loop antenna is not the best solution, and not only for its dimensions, which are very short with respect to the wavelength associated to the frequency of 2.4 GHz. In fact, with the aim of increasing the length of the radiating element, the number of loops has been increased, but neither the 4-loop, nor the double 4-loop antennas improve the performances in terms of gain and radiation efficiency, whose values decrease. Another family of structures, the dipole one, in three different topologies, has shown a gain increment. In particular, the bent-dipole shows the best performances of the considered set and a isotropic radiation pattern.

We observe, in conclusion, that the analysis reveals a poor radiation efficiency for all the examined topologies. On the other hand, an increase of gain and radiation efficiency has been reached with respect to the first radiating element. Although the dimensions of the antennas do not allow resonance conditions, and therefore their gain and radiation diagrams are of minor relevance for this application, nevertheless this does not seem to be a limit for the specific application in contactless sensing, where the creation of a short range communication channel is sufficient.

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