Input Impedance Measurement of a Dipole Antenna Mounted on a Car Tire

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Abstract

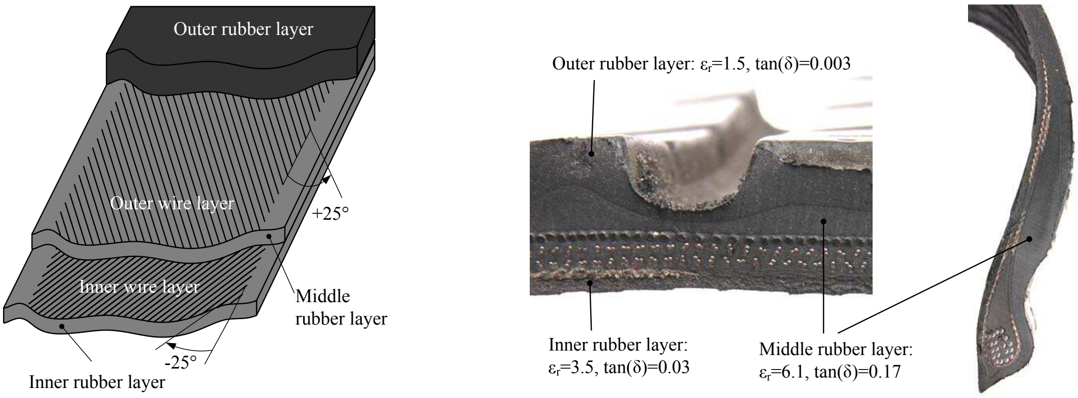
For the design of an antenna that will be directly attached to a car tire, the proximity effects due to the tire have to be considered. Measurements are performed on a dipole antenna that is mounted at the inside of the tire tread to determine the change in input impedance and resonant frequency caused by the dielectric rubber material and the metal reinforcement of the tire. A differential measurement setup with a vector network analyzer is presented to realize a symmetric antenna feed and to avoid a non-ideal balun. The measurement results are compared with simulations and good agreement is found.

1 Introduction

The antenna design for a wireless sensor unit that is attached to the inside of a car tire and will be used for a novel tire pressure monitoring system (TPMS) [1][2] needs a thorough investigation of the antenna's closest environment. The tire and the rim significantly influence the antenna parameters such as input impedance, radiation pattern, and gain [3]. Thus, the antenna designer needs to know the tire structure and the dielectric material properties of the tire rubber in the proximity of the antenna to evaluate the influence of the tire on the antenna. Especially, if the antenna is mounted directly on the tire rubber, the interaction with the rubber material is strong. Within this work, measurements and simulations of the input impedance versus frequency of a dipole antenna that is mounted directly on the tire rubber are presented and the proximity effects are evaluated. With the results obtained during this investigation an efficient design for an antenna attached to the tire rubber can be found. In Section 2, the tire structure is described. In Section 3, the input impedance measurement of the antenna is presented and the measurement results are compared to simulations. Section 4 lists the proximity effects arising from the tire tread. A conclusion is given in Section 5.

2 Tire structure

A tire consists of different rubber layers, metal, and fiber reinforcements. These components ensure the main functions of the tire: load carrying and transfer of acceleration, deceleration, and lateral forces [4]. From a radio frequency (RF) point of view one can divide a tire into two sections: sidewalls and the tread [3]. In a standard car tire the sidewalls are composed of rubber, fiber reinforcement, and a bead composed of steel wires. There are no further metallic parts in the sidewalls. In contrast to the sidewalls, the tread includes different rubber layers, fiber reinforcements, and also a metal reinforcement—the steel belt. Figure 1a shows the arrangement of the steel belt that consists of two parallel layers. These layers are composed of a large number of separate wires with a length of some $0.5\,\mathrm{m}$. In each layer the wires draw an angle of about plus and minus $25\,^{\circ}$ with respect to the direction of motion. Furthermore, adjacent wires are twisted into pairs. The pairs show a spacing of $1\,\mathrm{mm}$. Every wire has a diameter of $0.3\,\mathrm{mm}$. The steel belt layers form planes which allow an anisotropic current flow which is in parallel to the wires only. The different rubber layers of the tire can be considered as lossy dielectrics. In [5] measurements of the dielectric material parameters—relative permittivity ε_r and loss tangent $\tan(\delta)$—of each rubber layer of a standard tire are given. The results are shown in Figure 1b. The investigated standard tire is a Continental Premium Contact 2 205/55 R16 91V.



(a) Schematic model of tire tread

(b) Dielectric material parameters

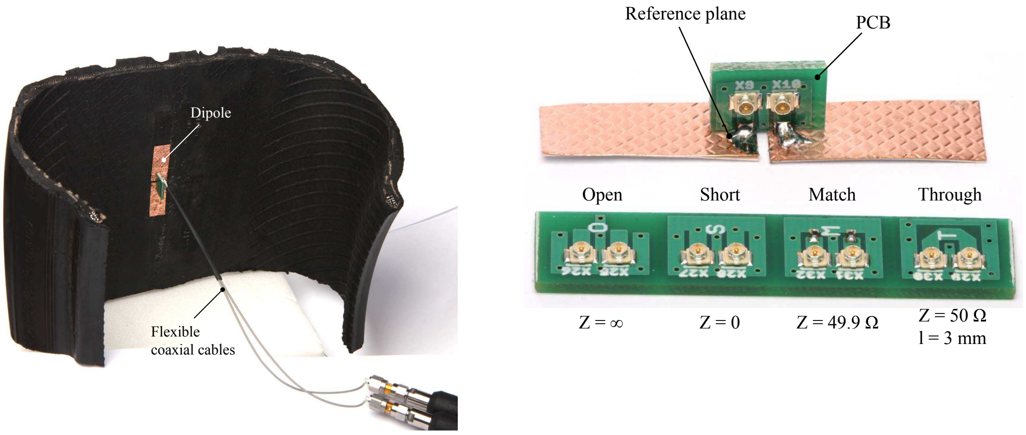
Fig. 1: Tire structure and dielectric material parameters

3 Measurement of antenna input impedance

To investigate the effects of the tire on an antenna, the input impedance of a dipole antenna is measured versus frequency. Figure 2a shows the measurement setup of the dipole mounted on a piece of the tire tread. The dipole is made of copper tape with non-conducting adhesive. It has a length of $l = 51\,\mathrm{mm}$ and a width of $w = 10\,\mathrm{mm}$. Its resonant frequency in free space is approximately $f \approx c_0/(2l) = 2.9\,\mathrm{GHz}$, where c_0 is the velocity of light.

With a vector network analyzer (VNA) the reflection coefficient at the input of the dipole is measured. An unsymmetric feed has to be avoided because it introduces common mode currents that will cause radiation by far stronger than the original radiation of the antenna [6]. With a differential measurement setup a symmetric feed is realized. Thus, there is no need to use a non-ideal balun. To perform balanced reflection coefficient measurements, a pair of physical VNA analyzer ports are combined to form one logical differential port. The dipole is fed by two flexible $50\,\Omega$ coaxial cables. They are connected to the antenna via miniature coaxial connectors (U.FL series by Hirose Electric Co. LTD.) mounted on a small printed circuit board (PCB) built of FR4 with a thickness of $1.6\,\mathrm{mm}$. The circuit board connects the coaxial cables with the dipole, this can be seen in Figure 2b. To maintain the symmetry of the dipole the coaxial cables are fixed with a heat shrink tube. The dipole is connected to the VNA (Rohde&Schwarz ZVA24) capable of true differential mode via SMA adapters and cables. A custom-built calibration kit made of FR4 substrate is used to shift the reference plane of the measurement directly to the dipole. The calibration of one logical port requires the calibration of both physical ports. Therefore, the calibration kit has two open, two short, two match, and one through. Figure 2b shows the calibration kit and lists the impedances and the electrical lengths of the defined standards.

In Figure 3a measurement and simulation results of the input impedance—real part R and imaginary part X—versus frequency f are depicted. The curves correspond to different rotation angles ϕ of the dipole with respect to the direction of motion. The dipole is mounted in axial direction of the tire for a rotation angle of $\phi = 90\,^\circ$. If the dipole draws an angle of $\phi = 65\,^\circ$ with respect to the direction of motion, then it is mounted orthogonal to the wires of the inner wire layer of the steel belt. An angle of $\phi = 115\,^\circ$ means that the dipole is orthogonal to the wires of the outer wire layer. A simplified simulation model of the tire tread is created in Ansoft HFSS to facilitate the evaluation of different antenna designs. The simulation design can be seen in Figure 3b. The different rubber layers are assumed to be planar and homogenous. The steel belt layers are modeled using anisotropically conducting planes. The sidewalls are not implemented, since they do not significantly influence the input impedance of the



(a) Measurement setup

(b) PCB soldered on dipole and calibration kit

Fig. 2: Input impedance measurement

antenna attached to the tread. From Figure 3 it can be seen that measurement and simulation results agree well and that the simulation model is highly applicable to investigate different antenna designs.

4 Proximity effects

Figure 3a shows that the resonant frequency of the dipole is strongly shifted towards lower frequencies to approximately $2.3\,\mathrm{GHz}$. The frequency shift is caused by the dielectric rubber material, which has a relative permittivity greater than free space. The high permittivity of the rubber material, especially of the inner rubber layer on which the antenna is mounted, allows the antenna miniaturization [7]. Additionally, the mounting angle ϕ affects the resonant frequency of the antenna. This is caused by differently strong capacitive coupling effects between the steel wires and the conductive material of the dipole.

The antenna designer has to consider these effects to optimize the antenna for best performance within the tire environment. If the antenna is mounted on the tire sidewall, where no wire layers are present, the proximity effects on the antenna parameters are less severe.

5 Conclusion

The tire rubber material and the steel belt in the tire tread significantly influence the antenna parameters. To visualize the proximity effects the input impedance of a dipole antenna is measured versus frequency. The presented measurement method uses a symmetric antenna feed and avoids a non-ideal balun. The measurements show a strong shift of the resonant frequency from $2.9\,\mathrm{GHz}$ to $2.3\,\mathrm{GHz}$. The antenna designer has to consider these effects when creating an antenna that is directly attached to the tire. To reduce detuning effects an antenna should be mounted on the tire sidewall.

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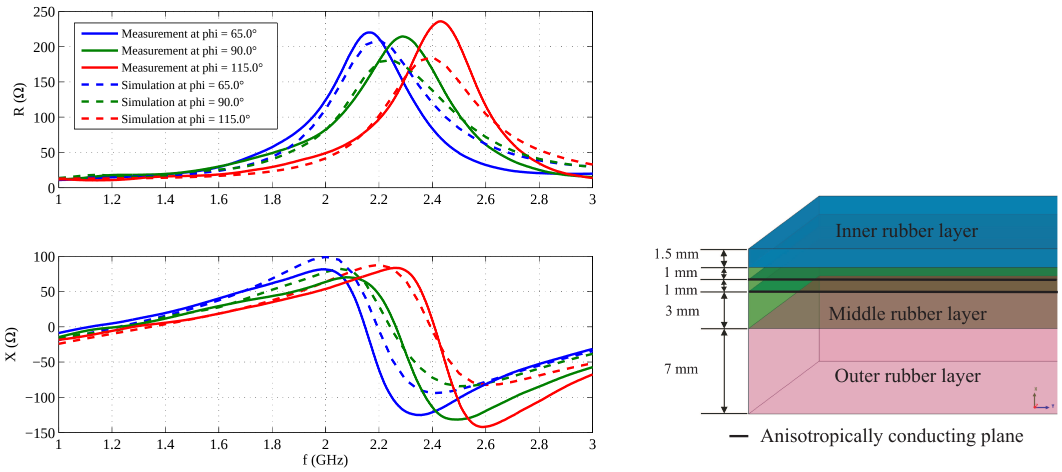

(a) Measurement and simulation results

(b) HFSS design of tire tread

Fig. 3: Measurement and simulation results of antenna input impedance versus frequency

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