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Published in:
Procedia Engineering

DOI:
10.1016/j.proeng.2016.11.319

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation for pulished version (APA):
Schimmack, M., Taute, W., & Höft, M. (2016). Modelling, Simulation and Experimental Analysis of a Metal-Polymer Hybrid Fibre based Microstrip Resonator for High Frequency Characterisation. *Procedia Engineering*, *168*, 975-978. https://doi.org/10.1016/j.proeng.2016.11.319

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 168 (2016) 975 – 978

Procedia Engineering

www.elsevier.com/locate/procedia

30th Eurosensors Conference, EUROSENSORS 2016

Modelling, Simulation and Experimental Analysis of a Metal-Polymer Hybrid Fibre based Microstrip Resonator for High Frequency Characterisation

Manuel Schimmack[a]*, Wolfgang Taute[b], Michael Hoeft[b]

[a]*Leuphana University of Lueneburg, Institute of Product and Process Innovation, Volgershall 1, D-21339 Lueneburg, Germany*
[b]*Kiel University, Institute for Electrical Engineering and Information Technology, Kaiserstraße 2, D-24143 Kiel, Germany*

Abstract

Conductive multifilament fibres are the fundamental core for wearable technology in the biomedical engineering fields, as conductors in sensors or in bio-sensing textiles for healthcare. This contribution presents a model, simulation and the experimental analysis of a metal-polymer hybrid fibre based microstrip resonator for high frequency characterisation. The high frequency electromagnetic field simulation (HFSS) by ANSYS® is used for the modelling and finite element based simulation. It follows the design and manufacturing of the metal-polymer hybrid fibre based microstrip resonator for analysis of the scattering parameter measurements and the quality factors to 10 GHz with a vector network analyser (VNA) by Rohde & Schwarz®. Simulations and analysis also compare solid matter wire with the metal-polymer hybrid fibre.

Keywords: microstrip resonator, resonator losses, quality factor, metal-polymer hybrid fibre, finite element simulation

1. Introduction

Wearable textile electronics will play an important role in the future for medical sensoring, safety and communication applications [1]. In this contribution, the manufactured multifilament fibres are composed of multiple conductive filaments. A single filament consists of a polyamide kernel and is surrounded by a thin silver

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* Corresponding author. Tel.: +49(0)4131-677-5309; fax: +49(0)4131-677-5300.
E-mail address: schimmack@uni-leuphana.de

doi:10.1016/j.proeng.2016.11.319

covering. The multifilaments are twisted together in an S and Z fashion to create dense and robust fibres. A possible model and measurement procedure for the impedance- and frequency characterisation, as a conductive textile transmission line, is presented in [2], [3] and [4]. Electrical characterisation of complex wearable stripline structures and its model are presented in [1] and [5]. In this contribution the model of the transmission resonator is used.

2. Modelling and Simulation

Figure 1 shows a general schematic of the transmission resonator as a two-port, with the characteristic impedance R(1+jΩ). Generally there is a resonance at multiples of the half wavelength. The HFSS model of the metal-polymer hybrid fibre based resonator is depicted in Fig. 2. The transmission characteristic of an electromagnetic wave and its electrical field in condition of the first resonance based on the finite element simulation is depicted in Fig. 3.

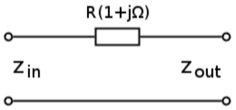

Fig. 1. Graphical representation of the transmission resonator formulated as two-port, with the impedance R(1+jΩ) in the vicinity of the resonance

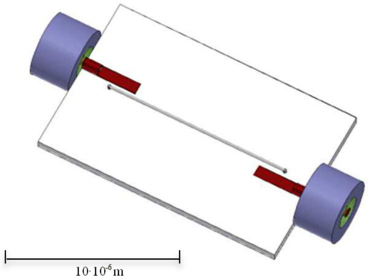

Fig. 2. Graphical representation of the HFSS model of the microstrip resonator and its components

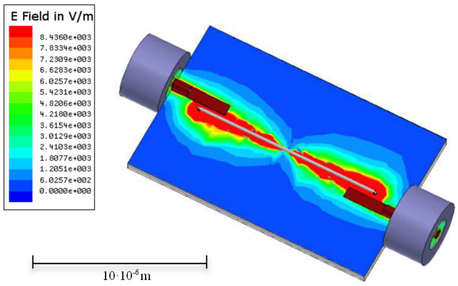

Fig. 3. The transmission characteristic of the electro-magnetic wave and its electrical field

The loading of the resonator by the input and output lines are described by the coupling factors

$$\beta_{in} = \frac{Z_{in}}{R}, \qquad (1) \qquad\qquad \beta_{out} = \frac{Z_{out}}{R}. \qquad (2)$$

With the implementation of (1) and (2) in the scattering matrix of the two-port it follows

$$[S] = \begin{bmatrix} \dfrac{R - Z_{in} + Z_{out}}{R + Z_{in} + Z_{out}} & \dfrac{2\sqrt{Z_{in} Z_{out}}}{R + Z_{in} + Z_{out}} \\ \dfrac{2\sqrt{Z_{in} Z_{out}}}{R + Z_{in} + Z_{out}} & \dfrac{R + Z_{in} - Z_{out}}{R + Z_{in} + Z_{out}} \end{bmatrix} = \begin{bmatrix} \dfrac{1 - \beta_{in} + \beta_{out} + j\Omega}{1 + \beta_{in} + \beta_{out} + j\Omega} & \dfrac{2\sqrt{\beta_{in}\beta_{out}}}{1 + \beta_{in} + \beta_{out} + j\Omega} \\ \dfrac{2\sqrt{\beta_{in}\beta_{out}}}{1 + \beta_{in} + \beta_{out} + j\Omega} & \dfrac{1 + \beta_{in} - \beta_{out} + j\Omega}{1 + \beta_{in} + \beta_{out} + j\Omega} \end{bmatrix}. \qquad (3)$$

Considering the metal-polymer hybrid fibre based resonator losses, it results in the unloaded quality factor in (4)

$$Q_0 = \frac{\omega_{res} L}{R}, \qquad (4) \qquad\qquad \Omega = Q_0 \upsilon. \qquad (5)$$

where ω is the resonance angular frequency. The normalized frequency is formulated by (5), where υ describes the detuning of the resonator. The loaded quality factor, which is measurable with the VNA, is defined as

$$Q_L = \frac{\omega_{res} L}{Z_{in} + R + Z_{out}} = \frac{\omega_{res} L}{R(1 + \beta_{in} + \beta_{out})} = \frac{Q_0}{1 + \beta_{in} + \beta_{out}}. \qquad (6)$$

The goal is to determine the loaded quality factor by the relation between the quotient of the measured resonance frequency and the 3 dB-bandwidth of the $|S_{21}|(f)$ curve. Considering the effective power of the measured insertion loss in detail

$$\left|S_{21}\right|^2 = \frac{4\beta_{in}\beta_{out}}{(1+\beta_{in}+\beta_{out})^2 + Q_0^2\upsilon^2} = \frac{4\beta_{in}\beta_{out}}{(1+\beta_{in}+\beta_{out})^2(1+Q_L^2\upsilon^2)} = T\,, \tag{7}$$

where T describes the transmission. The goal is to represent the transmission curve with the bandwidth $2\delta f$ by the Lorenz curve. It results in

$$T(f) = \frac{T(f_{res})}{1+Q_L^2\left(\dfrac{2\delta f}{f_{res}}\right)^2}\,. \tag{8}$$

The bandwidth of the measured resonance frequencies is analysed with the curve fitting toolbox in MATLAB®. It follows the loaded quality factor by (9), which is measured by (10)

$$Q_L = \frac{f_{res}}{2\delta f}\,, \tag{9}$$

$$T(f) = \frac{1}{2}T(f_{res})\,. \tag{10}$$

To determine the coupling factor, the effective power of the return loss S_{11} and the insertion loss S_{21} are considered as a function of the resonance frequency

$$\left|S_{11}\right|^2(f_{res}) = \frac{(1-\beta_{in}+\beta_{out})^2}{(1+\beta_{in}+\beta_{out})^2} \equiv \left|\Gamma_0\right|^2, \tag{11}$$

$$\left|S_{21}\right|^2(f_{res}) = \frac{4\beta_{in}\beta_{out}}{(1+\beta_{in}+\beta_{out})^2} \equiv \mathrm{T}_0\,. \tag{12}$$

It is possible to calculate the proportionality factor with (11) and (12)

$$1+\beta_{in}+\beta_{out} = 2\frac{1-\left|\Gamma_0\right|}{1-\left|\Gamma_0\right|^2 - T_0}\,. \tag{13}$$

Inserting (9) and (13) in (6) leads to the unloaded quality factor

$$Q_0 = Q_L(1+\beta_{in}+\beta_{out})\,. \tag{14}$$

Similar results can be obtained by defining external quality factors for loading the resonator with the impedances of the input and output lines instead of defining the coupling factors β_{in} and β_{out} [6].

3. Experimental analysis

Figure 4 shows the designed microstrip resonators for experimental analysis of the scattering parameters with the vector network analyzer by Rohde & Schwarz®. For the resonator substrate a Rogers TMM® 10 thermoset microwave laminate is used, which combines low thermal coefficient of dielectric constant, a copper matched coefficient of thermal expansion and dielectric constant uniformity. The simulated and the measured transmission coefficient of a silver wire based microstrip resonator is compared in Fig. 5. At 8 GHz the measurement exhibits a stronger damping and a discrepancy of the resonance frequency in comparison to the simulation result, caused by a short wire deformation. The same outcome is evident in Figure 6, which shows the simulated and measured transmission coefficient of the metal-polymer hybrid based microstrip resonator. The result is based on small variations of the distance between the fibres and the TMM laminate. In both cases the permeability declines, causing an increased resonance frequency. Nevertheless a good accordance between simulations and measurements is visible. An overview of the solid mater wire and metal-polymer hybrid fibre based microstrip resonator and its parameters is shown in Tab. 1.

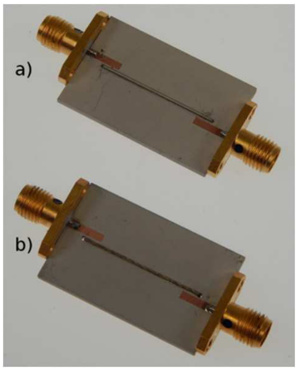

Fig. 4. Prototypes of the a) solid matter wire and b) the metal-polymer hybrid fibre based resonator

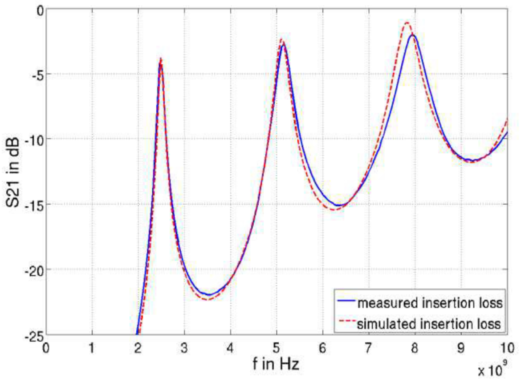

Fig. 5. Results of the simulated and measured insertion loss of the solid matter wire based microstrip resonator

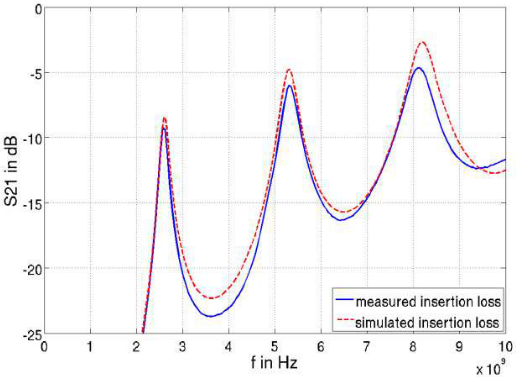

Fig. 6. Results of the simulated and measured insertion loss of the metal-polymer hybrid fibre based microstrip resonator

Tab. 1. Overview of the solid mater wire and metal-polymer hybrid fibre based microstrip resonator and its parameters

	Solid mater wire			Metal-polymer hybrid fibre		
Simulated resonance frequency f_{res}	$2.485 \cdot 10^9$ Hz	$5.095 \cdot 10^9$ Hz	$7.840 \cdot 10^9$ Hz	$2.600 \cdot 10^9$ Hz	$5.300 \cdot 10^9$ Hz	$8.200 \cdot 10^9$ Hz
Measured resonance frequency f_{res}	$2.506 \cdot 10^9$ Hz	$5.176 \cdot 10^9$ Hz	$7.988 \cdot 10^9$ Hz	$2.642 \cdot 10^9$ Hz	$5.410 \cdot 10^9$ Hz	$8.239 \cdot 10^9$ Hz
Loaded quality factor Q_L	23.703	18.739	15.082	14.150	14.979	11.161
Unloaded quality factor Q_0	89.047	97.430	99.567	22.604	31.745	30.346

4. Conclusion

This contribution presents a model, simulation and the experimental analysis of metal-polymer hybrid fibre based microstrip resonator for high frequency characterisation and sensing. The high frequency electromagnetic field simulation (HFSS) by ANSYS® is used for the modelling and finite element simulation. The design and manufacturing of the metal-polymer hybrid fibre based microstrip resonator for analysis of the scattering parameter measurements and the quality factors to 10 GHz is considered. For the resonator substrate a Rogers TMM® 10 thermoset microwave laminate is used, which combines low thermal coefficient of dielectric constant, a copper matched coefficient of thermal expansion and dielectric constant uniformity. Simulations and analysis also compare solid matter wire with the metal-polymer hybrid fibres. A good agreement between simulations and measurements is shown.

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