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Surface Impedance Estimation of a Stretchable Material

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Abstract

Stretchable materials are widely used for the realization of various sensors but their radio-frequency behavior is still little explored today. Here an innovative method is proposed that allows to derive the surface impedance of such materials. This parameter is fundamental for obtaining a calibration curve of these materials for their employment as a sensitive element. The proposed method allows to obtain the surface impedance of the material while it is being stretched and is based on a contact-less measurement of the scattering parameters. By exploiting these parameters and thanks to an inversion procedure, it is possible to obtain the value of the surface impedance as the frequency and strain vary.

1 Introduction

Strain sensors represent a largely investigated topic in the engineering field and numerous performing strain sensors have been designed [1, 2]. Most of these require an electrical contact for sensor reading. However in some situations it would be convenient to have completely wireless strain sensors. The idea is to create a wireless sensor that does not need the wiring system for reading. To do this, it is necessary to observe how the properties of the material under test vary when it is stretched. Therefore the materials used to make these sensors must be stretchable and their properties must vary as the strain level varies. The parameter that can be analyzed to study the variation of the properties of the material as the degree of strain varies is the surface resistance. Generally, the surface impedance of a material is obtained with the classic four-probe method which allows to derive the Direct Current (DC) surface impedance [3]. This method offers a good reliability but it is a contact method and can damage the sheet. Another problem is that the characterization performed in DC may not be valid or accurate at microwave frequencies. The ideal solution to avoid damaging the material is to carry out a contact-less measurement of the surface impedance. In the literature there are several methods for determining the surface impedance of a material but almost none of these is truly a contact-less method [4]. Microwave methods are mainly divided into resonant and non-resonant methods. Resonant methods show a good accuracy and sensitivity; however, they require an ad-hoc cavity and sample preparation can be complicated. Non-resonant methods are based on the measurement of the signal reflected and transmitted by the sample. These methods allow measurements to be made using different experimental setups and require fewer precautions [5]. In [6] a method has been proposed to derive the surface impedance of an ink deposited on a dielectric substrate, by using a rectangular waveguide and an inversion procedure to derive the surface impedance from the measured scattering parameters. A similar approach was used in [7]. Here, the discontinuity between the two waveguides is explicitly taken into account. In order to fabricate a strain sensor, it is necessary to test the resistivity of the material under different stretching conditions and thus the sensitive material should be not in contact with the flanges of the waveguide. A completely contact-less method was proposed in [8] . The measurement setup consists of two rectangular waveguides placed at a predetermined distance from each other. In order to obtain an accurate measurement of the surface impedance an electromagnetic bandgap (EBG) surface is positioned on one of the two flanges, which serves to prevent field leakage in correspondence of the gap. The surface impedance value is obtained thanks to an inversion procedure starting from the scattering parameters obtained by measurements. A further refinement of the method is shown in [9] . In this case the measurement setup is the same as the previous one but there is a change in the circuit model that takes into account the fact that the system, due to the presence of the EBG surface, is not symmetrical. This method offers an accurate estimate of the real part of the surface impedance of the sheet placed between the two waveguides, but gives a significant error on the imaginary part. Here a method is proposed that allows to limit the error on the imaginary part while maintaining a high accuracy on the real part. Here a different calibration measurement is proposed. The calibration is carried out with the sheet, whose surface impedance measurement is already known, placed in the middle between the two waveguides.

2 Proposed Experimental setup

Starting from what explained in [9], here a method for the contact-less characterization of stretchable materials is proposed.The proposed method consists of several steps which allow to determine the variation of the surface impedance of the material when it is stretched.The first step of the procedure consists in determining the surface impedance value of stretchable materials, in fact in the literature there

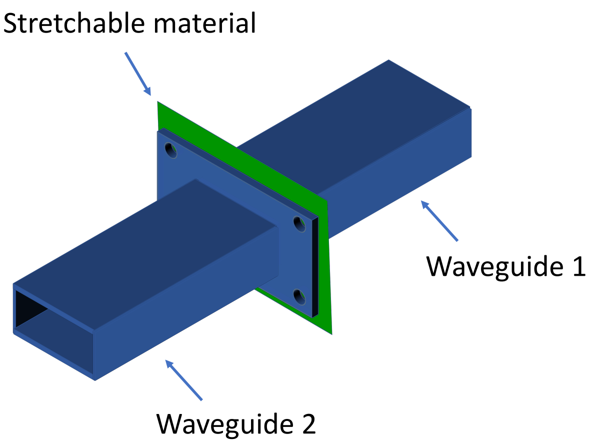


Figure 1. Closed waveguide measurement.

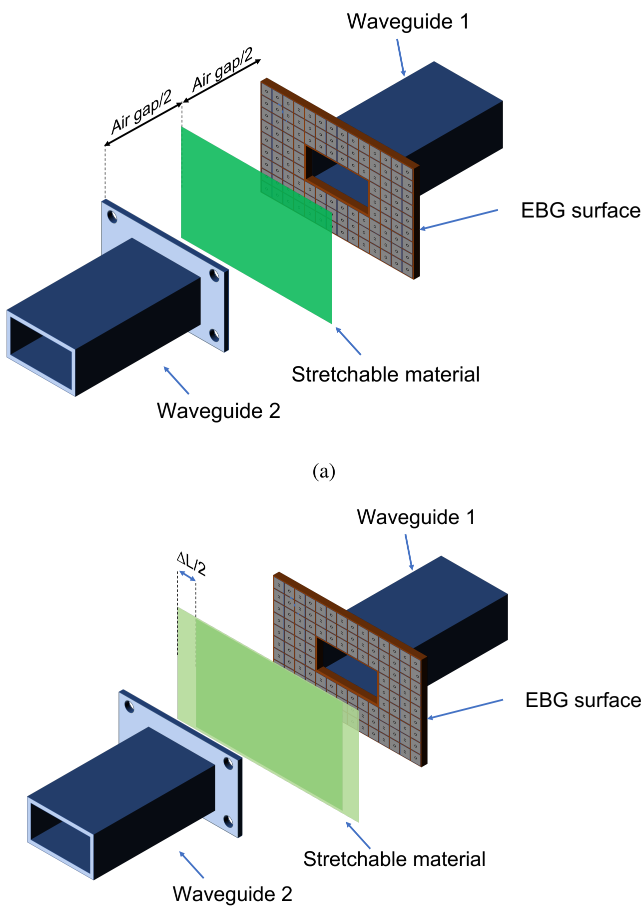
is no study about the radio-frequency characterization of such materials. Therefore, a closed waveguide measurement of the sample under test is carried out as shown in the Fig. 1. The value obtained with the close waveguide measurement can be taken as a reference for the subsequent steps of the procedure. The next step is to measure the surface impedance of the sheet in a completely contact-less way. In this case the measurement system is the one proposed in [9]. To carry out the contact-less measurement, two rectangular waveguides are used, separated by an air gap and the sheet is positioned in the middle. To reduce the field losses introduced by the air gap, an EBG surface is applied on one of the two waveguides. The measurement system is shown in Fig. 2.

The contact-less measurement of the surface impedance of the material is carried out at different strain values in order to be able to correlate the two quantities. To be able to estimate the variation in surface impedance as the strain varies, a two-step procedure is required. In the first, a calibration measurement is carried out. The calibration measurement is necessary to take into account the discontinuity between the two waveguides. Unlike what is shown in [9], the calibration measurement is performed with the sheet in the middle. The equivalent circuit of the calibration step is shown in figure in which the stretchable sheet is represented by a lumped parameter Y_s. Z and Y are the calibration parameters that take into account the discontinuity between the two waveguides.The calibration circuit can be described by using the *ABCD* matrix:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ Y_{d1} & 1 \end{pmatrix} \begin{pmatrix} 1 & Z_d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ Y_s^{cal} & 1 \end{pmatrix} \begin{pmatrix} 1 & Z_d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ Y_{d2} & 1 \end{pmatrix} \quad (1)$$

$$A = \frac{(1+S_{11})(1-S_{22})+S_{21}S_{12}}{2S_{21}} \quad (2)$$

$$B = Z_0 \frac{(1+S_{11})(1+S_{22})-S_{21}S_{12}}{2S_{21}} \quad (3)$$



(a)

(b)

Figure 2. (a) Calibration setup with the material in the unstretched phase in the middle. (b) Measurement setup for the contact-less estimation of the surface impedance when the material is stretched by $\Delta L = L - L_0$ (where L_0 is the original length and L is the final length).

$$C = \frac{1}{Z_0} \frac{(1-S_{11})(1-S_{22})-S_{21}S_{12}}{2S_{21}} \quad (4)$$

$$D = \frac{(1-S_{11})(1+S_{22})+S_{21}S_{12}}{2S_{21}} \quad (5)$$

Knowing the value of Z_s in the unstretched state, which we obtained from the closed waveguide measurement, and considering the relationships between the scattering parameters and the *ABCD* parameters, it is possible to obtain the analytical expression of the calibration parameters.

$$Z_d = \frac{-2 + \frac{\sqrt{2}\sqrt{2\ S_{21} + Y_s^{cal} Z_0 + S_{11} Y_s^{cal} Z_O - S_{21}^2 Y_s^{cal} Z_O + S_{22} Y_s^{cal} Z_O + S_{11}\ S_{22} Y_s^{cal} Z_O}}{\sqrt{S_{21}}}}{2 Y_s^{cal}} \quad (6)$$

$$Y_{d1} = \frac{1 - S_{11} - 2S_{21} + S_{21}^2 + S_22 - S_11S_{22} - 2S_{21}Y_s^{cal}Z}{2S_{21}Z(2 + Y_s^{cal}Z)} \quad (7)$$

$$Y_{d2} = \frac{1 + \mathrm{S}_{11} - 2\ \mathrm{S}_{21} + \mathrm{S}_{21}^2 - \mathrm{S}_{22} - \mathrm{S}_{11}\ \mathrm{S}_{22} - 2\ \mathrm{S}_{21}\mathrm{Y}_s^{\mathrm{cal}}\mathrm{Z}}{2\ \mathrm{S}_{21}\mathrm{Z}(2 + \mathrm{Y}_s^{\mathrm{cal}}\mathrm{Z})} \quad (8)$$

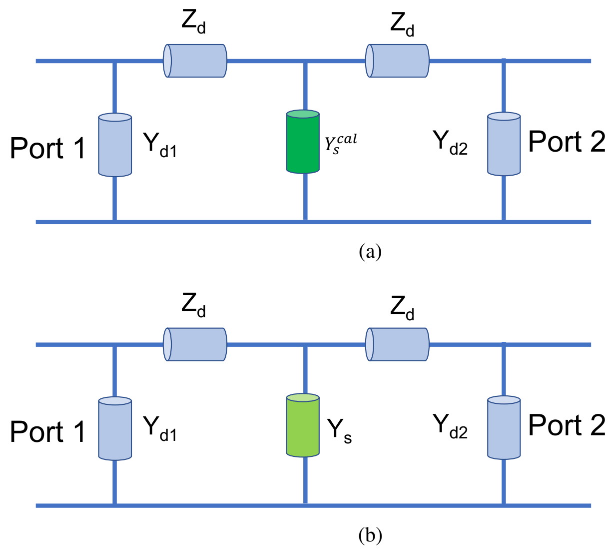


Figure 3. Equivalent circuit model with material in the (a) unstretched state (calibration circuit) and in (b) stretched state (b).

Subsequently, the sheet of material is stretched to various levels of strain. At this point, the objective is to obtain the new surface impedance value of the material in the stretched state. Now the equivalent circuit is shown in Fig. 3(a). Apparently the circuit is equal to the one proposed in Fig. 3(b). The difference is that in this second circuit the material is stretched and its surface impedance is different from the previous one. It is possible to obtain the new surface impedance value through an inversion procedure starting from the $ABCD'$ matrix:

$$\begin{pmatrix} A' & B' \\ C' & D' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ Y_{d1} & 1 \end{pmatrix} \begin{pmatrix} 1 & Zd \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ Y_s & 1 \end{pmatrix} \begin{pmatrix} 1 & Zd \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ Y_{d2} & 1 \end{pmatrix} \quad (9)$$

$$Z_s = \frac{S'_{21}\,(Z + Z_0 + Y_1 Z Z_0)\,(Z + Z_0 + Y_2 Z Z_0)}{-2S'_{21}Z + 2Z_0 - 2S'_{21}Z_0 - 2S'_{21}Y_1 Z Z_0 - 2S'_{21}Y_2 Z Z_0 - 2S'_{21}Y_1 Z_0^2 - 2S'_{21}Y_2 Z_0^2 - 2S'_{21}Y_1 Y_2 Z Z_0^2} \quad (10)$$

where Z_s is the surface impedance value when the material is stretched. In order to obtain the value of Z_s starting from (9) it has been assumed that the calibration parameters remain constant.

3 Numerical results

At first we tried to understand the benefits of using the calibration technique with the sheet placed between the two waveguides in order to characterize a sheet of material with unknown surface impedance. Then as a first step electromagnetic numerical simulations were performed using the CST Studio Suite software. The first results were obtained from the simulations carried out using the CST software. Two rectangular waveguides (WR137) were used in the simulations. These waveguides operate in the frequency range between 5.85 GHz and 8.20 GHz.To validate the model, a first simulation was made by using a calibration sheet with a surface impedance equal to 100 Ω/sq. From this simulation the scattering parameters were extracted and using the equations (2,3,4,5) we obtain the calibration parameters Z_d, Y_{d1} and Y_{d2}. After this first simulation, a parametric simulation was carried out in which the surface impedance value of the sheet placed between the two guides was varied. Using the S_{21} parameter of these simulations and the calibration parameters obtained in the previous step, using equations ((6,7,8)) the surface impedance value of the sheets under examination is obtained. From Fig. (4) it is possible to observe that using a surface impedance sheet equal to 100 Ω/sq for the calibration it is possible to accurately estimate the surface impedance of unknown sheets. In this case the estimate of the Zs of three sheets with surface impedance between 50 Ω/sq and 120 Ω/sq is shown. The estimate of the real part is very accurate but also the estimate of the imaginary part is precise unlike what happens in the case in which an empty calibration is performed.The fact that a calibration sheet with impedance equal to 100 Ω/sq can be used to accurately estimate the Zs of sheets with surface impedance between 50 Ω/sq and 100 Ω/sq suggests that this method is optimal for estimating the variation surface impedance of a sheet as its strain level varies.

4 Conclusion

In this work we have shown that it is possible to estimate the surface impedance of a thin sheet using, in the calibration step, a sheet of known surface impedance. Unlike what happened in [9], in this case it is possible to obtain a good estimate of both the real part and the imaginary part of the surface impedance. With this measurement method, the change in surface impedance of a sheet being stretched can be calculated. In fact, during the calibration phase, the value of the surface impedance of the sheet in the unstretched state can be used, which we assume is known as it can be obtained simply from the measurement in closed waveguide. Subsequently, the value of Z_s is estimated at different strain values. In this way it is possible to observe the variation of surface impedance as the strain varies.

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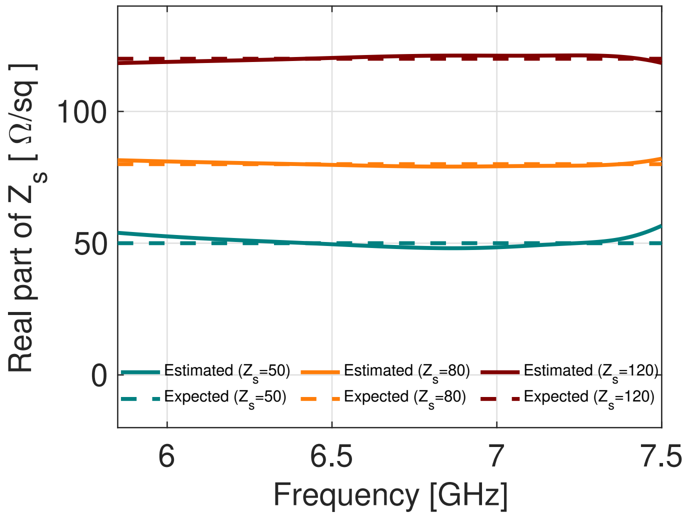
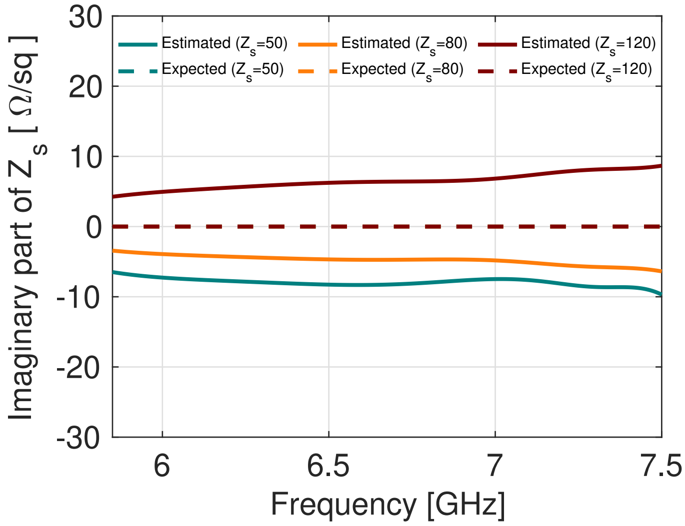


(a)



(b)

Figure 4. (a) Real part of the surface impedance, (b) Imaginary part of the surface impedance.

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