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A contactless measurement of the surface impedance of a thin sheet of material

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Abstract

Surface impedance value represents a crucial parameter for the characterization of thin sheets of material. A method for the estimation of this quantity that does not require a direct contact with the sample under test is proposed. The surface impedance is calculated through an inversion procedure that exploits the scattering parameters obtained from the proposed waveguide measurement setup. An inversion procedure based on the representation of the waveguide-air section-waveguide section as a T junction is employed. It is also shown that the absence of contact of the sample under test and the waveguide determines the leakage of electric fields which invalidate the inversion procedure. An improved configuration including an electromagnetic band-gap (EBG) structure is used to make the estimation of the surface impedance more accurate.

1 Introduction

Piezoresistive materials are widely used in many engineering fields for fabrication of sensors, such as force sensors [1], pressure sensors [2], strain sensors [3]. Most of the works in this sector deal with high performance sensors that are wired (*i.e.* sensor is connected to the reader via a cable). However, this can be sometimes a disadvantage in terms of sensor placement, cost and limitation in the operative scenario. Therefore, it could be interesting to investigate sensors that are able to operate *wireless*. For example, a new class of strain sensors able to provide a wireless reading of the sensed parameter could be designed by a proper use of piezoresistive materials. To this aim, it is fundamental to characterize the piezoresistive material within the frequency bandwidth used for their wireless interrogation (*e.g.* microwaves). This frequency range is seldom considered in the characterization of such materials that are generally employed in devices that operate at much lower frequencies. It is therefore essential to have a reliable estimate of the material behavior in unexplored frequency bands. Moreover, it is also important to be able to accurately estimate the surface impedance of the piezoresistive sheet when it is stretched at different degree in order to correlate this parameter with the strain in the correspondent sensor calibration curve.

There are several methods to derive the surface impedance of a thin sheet. The most used method to derive the DC surface impedance of a thin sheet is the four-point method which has the disadvantage of being a contact method and can damage the material sample [4]. Microwave methods have been extensively studied and can be used as contactless measurement methods. The microwave methods are mainly divided into resonant and non-resonant methods. Resonant methods have 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 using rectangular waveguide and using an inversion procedure to derive the surface impedance starting from the measured scattering parameters. A similar approach was used in [7]. Here, the discontinuity between the two waveguides is taken into account. The aforementioned methods offer a good estimate of the surface impedance of the investigated sample however, as already pointed out, in order to fabricate a strain sensor, it is necessary that the piezoresistive sheet is not in contact with the flanges of the waveguides. Indeed, the thin sheet must be deformed and at the same time the surface impedance must be measured.

In this work a novel setup has been developed that allows to perform a contactless surface impedance measurement in which there is an air gap between the two waveguides and the piezoresistive sheet. The proposed setup solves the issues of contactless characterization procedures by introducing an electromagnetic band-gap (EBG) surface on one of the two flanges to achieve a better control of the interaction between the probing field and the sample.

2 Proposed measurement method

The proposed method takes inspiration from the approach proposed in [5, 6] in which two waveguides were used for the measurements and a thin sheet was placed in the middle (Figure 1). However, unlike the former setup in which the thin sheet was in contact with the flange of the waveguide, in the proposed setup a contactless characterization of the sample is attempted by allowing an air gap between the two flanges where the tested thin sheet can be placed. This configuration, removing the need of waveguide to sample contact, allows the characterization of piezoresistive samples at radio frequencies while the sample is stretched.

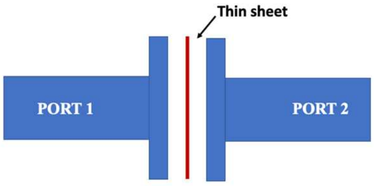
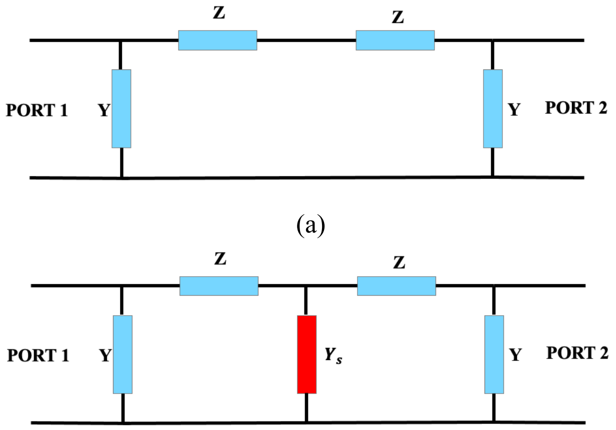


Figure 1. Measurement setup

The method for determining the surface impedance, according to [6], is divided into two steps. In the first one, an unloaded measurement is performed. This is allows calibrating the system determining the parameters of the equivalent circuit shown in Figure 2. (a). Since the system is perfectly symmetrical it can be assumed that the two parallel admittances (Y) are equal. The same can be said for the two series impedances (Z). In the second step, the thin sheet is introduced between the two flanges (Figure 2. (b)). The thin sheet can be modeled as a lumped parameter Y_s that represents the inverse of the surface impedance. Once the impedances and the admittances obtained in the calibration step are known, it is possible to obtain the surface impedance of the sheet using an inversion procedure.



(a)

(b)

Figure 2. Equivalent circuit models: (a) calibration of the gap and (b) final model with the thin sheet.

The circuit model can be described using the ABCD parameters. The ABCD matrix of the circuit for the first step is as follows:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \tag{1}$$

$$= \begin{bmatrix} 1+2ZY & 2Z \\ 2Y\alpha & 1+2ZY \end{bmatrix},$$

where $\alpha = (ZY + 1)$.

Starting from the matrix in (1) and exploiting the relationships between the scattering parameters and the ABCD ones, it is possible to obtain Z and Y from the following equations:

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

$$C = \frac{1}{Z_0} \frac{(1-S_{11})(1-S_{22}) - S_{12}S_{21}}{2S_{21}} = 2Y\alpha \tag{3}$$

where Z_0 is the characteristic impedance of the TE_{10} mode in the waveguide.

Since the system is symmetrical, it is possible to assume that S_{11} is equal to S_{22} and that S_{21} is equal to S_{12}. Z and Y are obtained as:

$$Z = Z_0 \frac{(1+S_{11})^2 - {S_{21}}^2}{4S_{21}} \tag{4}$$

$$Y = \frac{-2 + \sqrt{4 + 8Z((1-S_{11})^2 - S_{21})}}{4Z} \tag{5}$$

After inserting the thin sheet between the waveguides, the ABCD matrix changes as follows:

$$\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Ys & 1 \end{bmatrix} \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \tag{6}$$

From (6), after some analytical manipulations, it is possible to derive the surface impedance Z_s of the sheet analytically as:

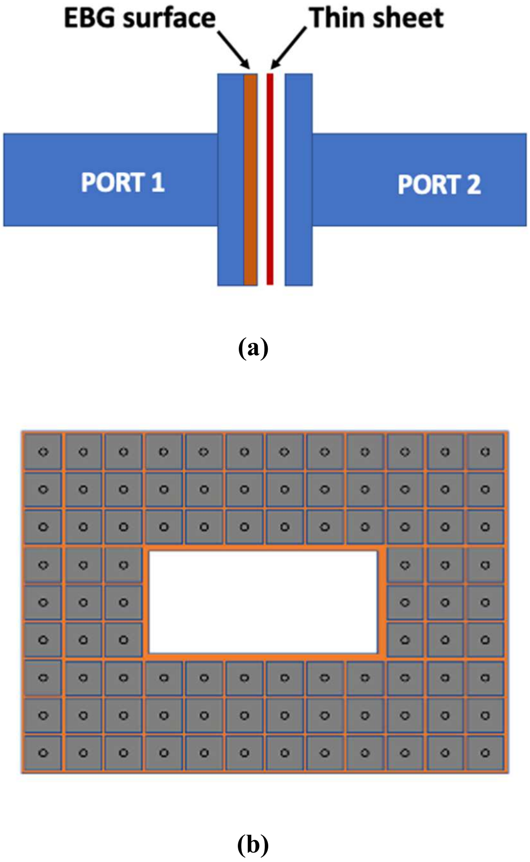
$$S'_{21} = \frac{2}{A' + \frac{B'}{Z0} + C'Z0 + D'} \tag{7}$$

$$Z_s = -\frac{Z(1+\alpha+ZY) + Z_0(ZY + ZY\alpha + 1) + \frac{Z^2}{Z_0}}{4ZY + \frac{2Z}{Z_0} + 2Z_0Y\alpha - \frac{2}{S'_{21}} + 2} \tag{8}$$

The presented inversion procedure, which is based on the initial calibration step as proposed in [6], revealed to be not sufficiently accurate when the sheet is not in contact with the waveguide. The introduction of the gap between the sheet and the waveguides leads to a significant error in the estimation of the surface impedance. This error is due to the presence of an air gap between the flange and the thin sheet which is responsible for a strong leakage of electric field.

To overcome this problem, it was decided to insert an EBG surface on one of the two flanges. The EBG is used to prevent the field leakage at the gap between the two waveguides. The unit cell of the EBG surface has been suitably engineered in order to achieve bandgap properties within the operating range of the waveguide. The advantage of introducing the EBG surface is to confine the field, limiting, the leakage across the gap.

The new configuration is shown in Figure 3. The procedure for deriving the surface impedance remains the one described above. The presence of the EBG just improve the applicability of the model (8). The EBG surface comprises periodic disposition of a square patches on a FR4 substrate connected to the ground plane trough a vias. The thickness of the substrate, the size of the patch and the radius of the vias have been sized in such a way as to have a band-gap in the frequency range of interest.



(a)

(b)

Figure 3. (a) Modified setup with EBG surface placed on the waveguide flange. (b) Top view of the EBG surface.

3 Numerical results

The accuracy of proposed characterization methodology has been evaluated by using numerical electromagnetic simulations. Simulations were carried out using the CST Studio Suite for assessing the reliability of the proposed procedure. A WR137 waveguide has been used, which operates in the frequency range [5.85-8.20 GHz]. The waveguide has a cut-off frequency of 4.301 GHz and the inner dimensions of the waveguide are 34.85 mm x 15.80 mm. The distance between the two waveguides has been set at 5 mm to allow the insertion of the thin sheets to be characterized.

After the initial calibration step which the parameters Z and Y characterizing the junction has been derived according to the procedure described in section 2. Subsequently, a thin sheet of known surface impedance was inserted between the two waveguides. A parametric study was performed, and the surface impedance was varied between 20 and 100 Ω/sq. The surface impedance Z_s is finally estimated by using relation (8).

Both the results with and without the use of the EBG has been derived. Without the use of EBG the model does not offer a good estimate of the surface impedance due to leakage across the gap. As it can be seen in Figure 4 and Figure 5, the introduction of EBG leads to a significant improvement in the estimation of the surface impedance. The use of EBG allows to reduce the error of below the 10% on the estimate of the surface impedance. The residual error is attributed to the assumption that Z and Y remain constant after inserting the sheet. The inversion method allows to calculate the surface impedance starting from a correct estimation of the transmission coefficient S_{21}.

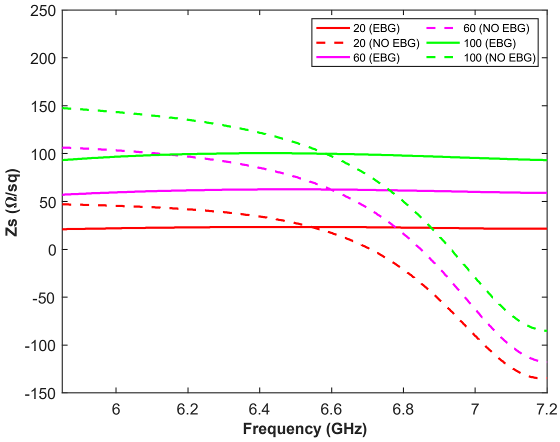


Figure 4. Real part of estimated surface impedance. Comparison between configuration with and without EBG is reported.

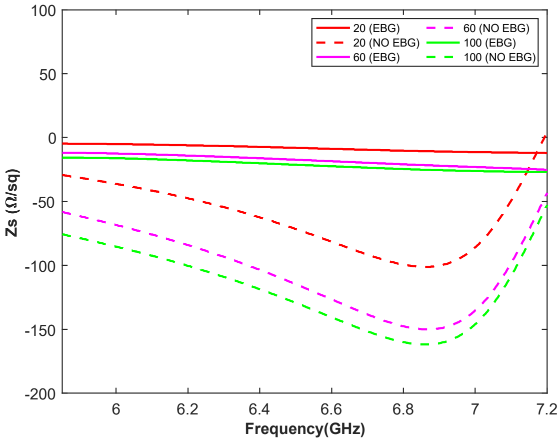


Figure 5. Imaginary part of estimated surface impedance. Comparison between configuration with and without EBG is illustrated.

4 Conclusions

A method for a contactless measurement of the surface impedance has been proposed for the first time. The proposed approach, due to absence of electrical contact, allows the characterization of piezoresistive material while they are stretched. However, the air gap introduced between the sheet and the waveguides leads to a field leakage which has been prevented by using an EBG surface. Results obtained from both experimental setups are compared. To obtain a more accurate measurement, the change of Z and Y parameters with respect to the surface impedance value should be taken into account.

5 References

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