EBG waveguides for contactless surface impedance measurements

Sandra Rodini, Simone Genovesi, Giuliano Manara, Filippo Costa*
Dipartimento di Ingegneria dell’Informazione, 56122, Università di Pisa, Italy.

*filippo.costa@unipi.it

Abstract. A method for the estimation of sheet impedance of thin sample which does not require a direct contact with the sample under test is proposed. The surface impedance is calculated through an inversion procedure exploiting the scattering parameters obtained through a waveguide measurement setup. An inversion procedure based on the representation of the waveguide-air-waveguide section as a π junction is employed. In order to prevent the field leakage from the air gap created for hosting the thin sheet, an EBG surface is introduced on the flange of the waveguide. It is shown that the introduction of the EBG surface remarkably improves the estimation of the surface impedance of the thin sheet with respect to the case without EBG.

1. Introduction
There exist 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 [1]. Microwave methods are mainly divided into resonant and non-resonant ones. 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 [2]. In [3] 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 [4] where the discontinuity between the two waveguides is taken into account. The aforementioned methods offer a good estimate of the surface impedance, but they require a physical contact with a waveguide. The aim of this paper is instead to develop an approach allowing the characterizations of thin sheet without a direct contact with the measuring fixture. Such a novel characterization setup would allow to estimate the surface impedance of the piezoresistive sheets under different stretching conditions and correlate this parameter with the strain in the correspondent sensor calibration curve. Piezoresistive materials are widely used in many engineering fields for fabrication of sensors, such as force sensors [5], pressure sensors [6], strain sensors [7]. 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, it could be interesting to investigate sensors able to operate wireless thus creating 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.
In this scenario it is important to consider that the presence of an air gap between the two waveguides introduces a different configuration of the field. For this reason, it is proposed to use an electromagnetic band-gap (EBG) surface to limit the harmful effects introduced by the air-gap.

2. Proposed measurement

The proposed method is based on a Transmission Line (TL) setup formed by two waveguides and a thin sheet which is placed in the middle, similarly to [5, 6]. However, unlike the former setups in which the thin sheet was in contact with the flange of the waveguide, here a contactless characterization of the sample is attempted by allowing an air gap between the two flanges. This configuration, removing the need of a contact between the waveguide and the sample, allows the wireless characterization of piezoresistive samples at radio frequencies while the sample is stretched. However, in the above-mentioned configuration there is a significant leakage of field between the flanges of the two waveguides. The field leakage is due to the presence of the air-gap and it is responsible for an inaccurate estimate of the surface impedance of the sheet under test.

The use of the EBG surface limits the leakage of electric field in the air gap and this positively impacts the estimation of the surface impedance. The proposed setup is shown in Figure 1. On one flange of the waveguide an EBG surface is applied. The top view of the EBG surface is shown in Figure 1. Figure 1(a) shows how the employment of the EBG surface modifies the electric field distribution. The field distribution is displayed at the center of the EBG stopband, that is 6.5 GHz. A similar field distribution is observed from 5.8 GHz to 7.2 GHz.

![Figure 1](image1.png)

**Figure 1.** (a) Modified setup with the EBG surface placed on the waveguide flange. (b) Top view of the EBG surface. Distribution of the electric field: (c) configuration without the EBG surface, (d) configuration with the EBG surface at 6.5 GHz.

The unit cell of the EBG surface has been suitably engineered in order to achieve bandgap properties within the operating range of the waveguide. In order to create an EBG surface that guarantees the necessary field confinement, a parametric study on the dispersion diagram has been carried out to tailor the unit cell size of the EBG. The parameters that were taken into consideration for the study of the dispersion diagram were: the size of the square patch, the radius of the vias, and the thickness of the substrate. In order to adapt the EBG surface to the waveguide flange, a periodicity $D=5.27$ mm was chosen. Regarding the thickness of the substrate, it is worth noting that the band-gap shifts towards lower frequencies at the increasing of the thickness. Since the range of frequencies of interest is up to 8 GHz, a substrate thickness of 1.6 mm has been chosen. A via radius equal to 0.25 mm was selected although changing the radius of the vias does not significantly affect the width of the stop band. The square patch side length has been fixed to 5 mm since larger dimensions (reduced gap size) would move the stopband to lower frequencies.

The method for determining the surface impedance, according to [6], is divided into two steps. The first step consists of an unloaded measurement aimed at calibrating the system and determining the parameters of the equivalent circuit shown in Figure 2. The two series impedances $Z$ are assumed to be identical but the same cannot be presumed for the two parallel admittances ($Y_1$, $Y_2$), because one ($Y_1$) is affected by the presence of the EBG surface. In the second step of the procedure, the thin sheet is introduced between the two flanges (Figure 2). The thin sheet can be modeled as a lumped parameter $Y_s$ that represents the inverse of the surface impedance. Once $Z$, $Y_1$, $Y_2$ obtained in the

---

2
calibration step are known, it is possible to obtain the surface impedance of the sheet using an inversion procedure.

![Figure 2. Equivalent circuit models: (a) calibration setup and (b) final model with the thin sheet.](image)

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

\[
\begin{bmatrix}
A & B \\
C & D \\
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
Y_1 & 1 \\
\end{bmatrix} \begin{bmatrix}
1 & Z_1 \\
1 & 0 \\
\end{bmatrix} \begin{bmatrix}
1 & 0 \\
Y_2 & 1 \\
\end{bmatrix} = \begin{bmatrix}
1 + 2ZY_2 & 2Z \\
1(2ZY_1 + 1) + Y_1 & 1 + 2ZY_1 \\
\end{bmatrix}
\]

Starting from the matrix in (1) and exploiting the relationships between the scattering parameters and the ABCD ones, it is possible to obtain \( Z, Y_1 \) and \( Y_2 \) as follow:

\[
Z = Z_0 \frac{(1 + S_{11})(1 + S_{22}) - S_{21}^2}{4S_{21}}
\]

\[
Y_1 = \frac{2S_{21}}{2Z} \frac{(1 + S_{11})(1 - S_{22}) + S_{21}^2}{1 - 1}
\]

\[
Y_2 = \frac{2S_{21}}{2Z} \frac{(1 + S_{11})(1 - S_{22}) + S_{21}^2}{1 - 1}
\]

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

\[
\begin{bmatrix}
A' & B' \\
C' & D' \\
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
Y_1 & 1 \\
\end{bmatrix} \begin{bmatrix}
1 & Z \\
1 & 0 \\
\end{bmatrix} \begin{bmatrix}
1 & 0 \\
Y_1 & 1 \\
\end{bmatrix} \begin{bmatrix}
1 & 0 \\
Y_2 & 1 \\
\end{bmatrix}
\]

Considering the expression of \( S_{21}^2 \) as a function of \( A', B', C' \) and \( D' \), it is possible to derive the value of \( Z_s \) as the inverse of \( Y_2 \).

3. Numerical results

The accuracy of proposed characterization methodology has been evaluated by using numerical electromagnetic simulations.

![Figure 3. (a) Real (b) imaginary part of estimated surface impedance. Comparison between configuration with and without EBG is reported.](image)
Simulations were carried out using the CST Studio Suite. A WR137 waveguide has been used, which operates in the frequency range [5.85-8.20 GHz]. The distance between the two waveguides has been set at 5 mm to allow the insertion of the thin sheets to be characterized. The parameters $Z, Y_1$ and $Y_2$ modelling the junction have been derived according to the procedure described in section 2. Subsequently, a thin sheet of known surface impedance was inserted between the two waveguides. The surface impedance $Z_s$ is finally estimated by using the relation obtained from the inversion procedure starting from (6). Figure 3 shows the estimates of three different real valued impedances (i.e. 20, 60 and 100 $\Omega$/sq) and proves the advantage achieved through the use of the EBG surface. The imaginary part is considered to be zero as it is common in practical resistive materials such as graphene, ITO and carbon loaded materials [7]. Without the use of EBG surface the model does not offer a good estimate of the surface impedance due to leakage across the gap. The introduction of EBG leads to a significant improvement in the estimation of the surface impedance. The residual error is attributed to the assumption that $Z$ and $Y_1$ and $Y_2$ remain constant after inserting the sheet. The inversion method allows to calculate the surface impedance starting from a correct estimation of the transmission coefficient $S_{21}$.

4. Conclusion
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 materials while they are stretched. The harmful effect introduced by the air gap between the sheet and the waveguides determined by the field leakage has been prevented by using an EBG surface on the waveguide flange.

5. Acknowledgements
This work was partially supported by the Italian Ministry of Education and Research (MIUR) in the framework of the CrossLab project (Departments of Excellence) and PRIN2017 GREEN TAGS “Chipless radio frequency identification (RFID) for GREEN TAGging and Sensing” (2017NT5W7Z).

References
[1] van der PAUW, L. J. "A method of measuring specific resistivity and hall effect of discs of arbitrary shape." *Semiconductor Devices: Pioneering Papers*. 1991. 174-182.
[2] F. Costa, M. Borgese, M. Degiorgi, and A. Monorchio, “Electromagnetic Characterisation of Materials by Using Transmission/Reflection (T/R) Devices,” *Electronics*, vol. 6, no. 4, p. 95, Nov. 2017, doi: 10.3390/electronics6040095.
[3] F. Costa, “Surface Impedance Measurement of Resistive Coatings at Microwave Frequencies,” *IEEE Trans. Instrum. Meas.*, vol. 62, no. 2, pp. 432–437, Feb. 2013, doi: 10.1109/TIM.2012.2217661.
[4] X.-C. Wang, A. Diaz-Rubio, and S. A. Tretyakov, “An Accurate Method for Measuring the Sheet Impedance of Thin Conductive Films at Microwave and Millimeter-Wave Frequencies,” *IEEE Trans. Microw. Theory Tech.*, vol. 65, no. 12, pp. 5009–5018, Dec. 2017, doi: 10.1109/TMTT.2017.2714662.
[5] X. Y. Liu, M. O’Brien, M. Mwangi, X. J. Li, and G. M. Whitesides, “Paper-based piezoresistive MEMS force sensors,” in *2011 IEEE 24th International Conference on Micro Electro Mechanical Systems*, Cancun, Mexico, Jan. 2011, pp. 133–136, doi: 10.1109/MEMSYS.2011.5734379.
[6] I. Baldoli, M. Maselli, F. Cecchi, and C. Laschi, “Development and characterization of a multilayer matrix textile sensor for interface pressure measurements,” *Smart Mater. Struct.*, vol. 26, no. 10, p. 104011, Oct. 2017, doi: 10.1088/1361-665X/aa644e.
[7] C. Yan *et al.*, “Highly Stretchable Piezoresistive Graphene-Nanocellulose Nanopaper for Strain Sensors,” *Adv. Mater.*, vol. 26, no. 13, pp. 2022–2027, Apr. 2014, doi: 10.1002/adma.201304742.