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Reflection based Strain Sensing using Metamaterials

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Keywords

Sensory Metamaterials, Resonator Arrays, Microwave Sensors, Lightweight Structures, Structural Health Monitoring

Abstract

Resonator arrays of periodicially arranged electromagnetic sub-wavelength resonators show a strong frequency filter behaviour which can be controlled by the geometry, size and arrangement of the resonators. The use of several resonator arrays and their integration into a polymer matrix allows the realisation of metamaterials with a specific resonance behaviour. The resonance behaviour can be influenced by material and structural changes enabling a passive sensor function. The considered sensor approach based on metamaterials is investigated to enable structural health monitoring of lightweight structures. In the present case, a double-layer Jerusalem cross (JC) resonator array (RA) is integrated into a glass fibre reinforced plastic (GFRP) to analyse the change of the resonance behaviour under load (strain) using a reflection measurement. The CST (Computer Simulation Technology) Microwave Studio was used to model the resonator array for operation in the microwave frequency range between 15 GHz and 35 GHz as well as for the numerical analysis of the resonance behaviour under load. The numerical results were validated by a tensile test using a tensile test machine (type TIRATEST 28100, Tira GmbH) and by a reflection measurement using two standard gain horn antennas (type Standard Gain Horn Series 862, ARRA Inc) and a vector network analyser (type ZVA50, Rohde&Schwarz). The reflection measurement shows a reflection minimum at 28.6 GHz which moves to higher frequencies under load of the GFRP laminate. With the shift of the minimum, the quality factor decreases and the dip widens. The investigation shows that it is possible to provide a GFRP laminate with a specific electromagnetic behaviour by integrating resonator arrays. It is also shown that the specific electromagnetic behaviour can be influenced by structural changes and thus opens up the possibility of monitoring the condition of lightweight structures.

1 Introduction

The use of lightweight structures is one of the today's key technologies to save weight, energy and resources and therefore makes them particularly interesting for applications in the automotive industry, aerospace and rail transport. Lightweight structures are also used in civil and mechanical engineering as well as in energy technologies such as wind power plants [1]. Therefore, it is necessary to monitor the condition of these structures during the production process and during operation, whereby non-destructive methods are preferred. Condition monitoring of lightweight structures, especially of fibre composite structures, enables early detection of structural weaknesses that can result, for example,

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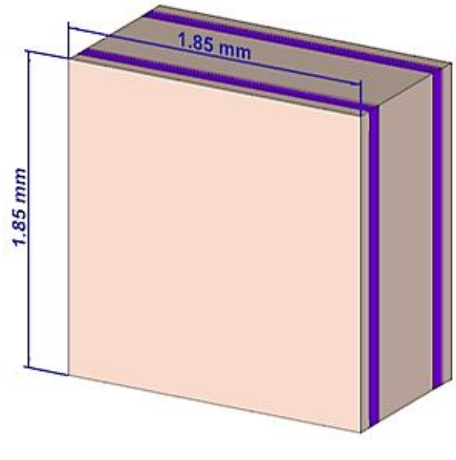
from de-bonding processes, inter-laminar fractures, fatigue, material defects and impacts and thus have a negative effect on stiffness and reliability [2-4]. A common way is to use wired sensors like strain gauge sensors [5-7], piezo resistive sensors [8] [9], fibre optics [10] [11] or alternatively surface acoustic wave technology [12-14] for condition monitoring. All these solutions require the integration of additional electronic components for power supply and data transfer. An alternative possibility for passive condition monitoring of lightweight structures is the use of metamaterials. In [15], a passive metamaterial made of split ring resonators (SRRs) that provides resonances with a high quality factor and large transmission dips is used to measure mechanical deformations wirelessly via a transmissions measurement. In [16], nested split ring resonators (NSRRs) coupled to an external antenna in their near field are used to remotely monitor submicron displacements over millimetre ranges.

In this work, a metamaterial-based sensor approach for the wireless detection of strain and structural defects is investigated. The sensor approach enables passive condition monitoring of lightweight structures made of GRFP by evaluating the resonance behaviour. For this purpose, resonator arrays are integrated into the lightweight structure. Furthermore, the investigated sensor approach allows a contactless and non-destructive reading of the status via a reflection measurement by means of electromagnetic waves. The resonator arrays serve as an essential element for the realisation of the passive sensor function in the microwave range. The resonator array consists of a variety of sub-wavelength resonators, which are periodically positioned in relation to each other. The resonator array generates a strong frequency filter response caused due to electromagnetic resonances that can be controlled by the dimension, geometry, alignment and arrangement of the resonators.

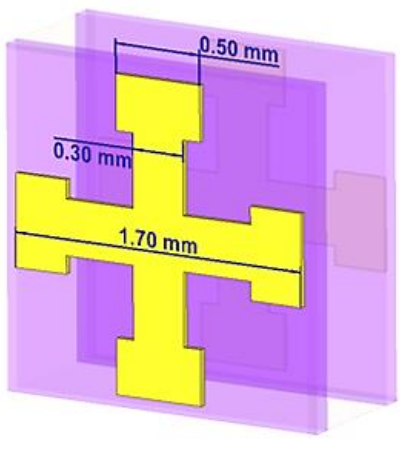
2 Design, Numerical Analysis, Fabrication and Experimental Validation

2.1 Design

The design of the sensor is supported by numerical analysis using the CST Microwave Studio® (CST). The CST software allows the simulation of infinitely extended two-dimensional periodic structures by considering only a single repeating element, the so-called unit cell. To perform a numerical analysis of the wireless strain sensing via a reflection measurement, a unit cell with a dimension of 1.85 mm x 1.85 mm and an overall layer thickness of 1.3 mm made of GFRP material and two integrated JC resonator arrays is considered. The two arrays have a distance of 0.6 mm from each other and are each covered with a 100 µm thick layer of GFRP. The space between the resonator arrays is also filled with GFRP (Figure 1a). The GFRP material is simulated using a FR-4 material with losses. The applied FR-4 material has a relative permittivity ε_r of 4.3 and a loss factor (tan δ) of 0.025. The modelled JC resonator, which is centrically located on top of a polyimide substrate, has a lateral dimension of 1.7 mm. The width of the conductive structure is equal to 300 µm. At the open ends of the cross structure, the conductive structure expands. The length of the expansion is 300 µm and the width 500 µm. The conductive layer consists of copper with a conductivity of 59.6×10^6 S/m. The used polyimide substrate has a relative permittivity of 3.5 and a loss factor of 0.0027.



a)



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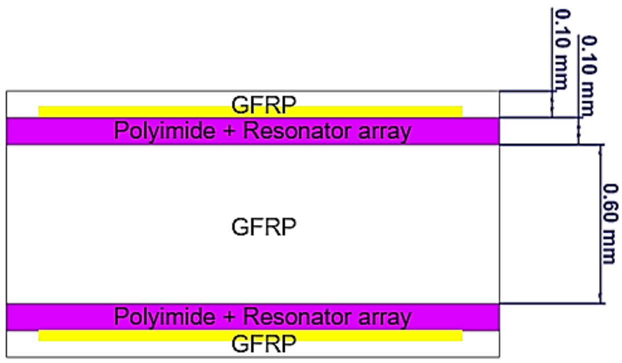


c)

Figure 1: The designed unit cell model of the considered sensor approach for wireless strain sensing shows a) the 3D model of the designed unit cell, b) the double layer JC resonator (array) integrated into the GFRP material and c) the cross-section through the GFRP sample

The double layer resonator array structure shown in Figure 1c was chosen to create a reflection minimum in the reflection response that can be detected via a reflection measurement. In addition, the designed JC resonator array consists of closely coupled resonators to obtain a strong electromagnetic coupling, which leads to a high sensitivity to structural changes, as is expected in the case of tensile stress.

2.2 Numerical analysis

In the case of elongation of the functionalised GFRP, it is assumed that the distance between the resonators of the integrated resonator arrays increases with the action of a tensile force, as shown in Figure 2. The greater the tensile force, the greater the increase in distance. In this simple numerical consideration a change of the metallic structures (enlargement, deformation) is not considered, because no information about the strain behaviour is available at the moment.

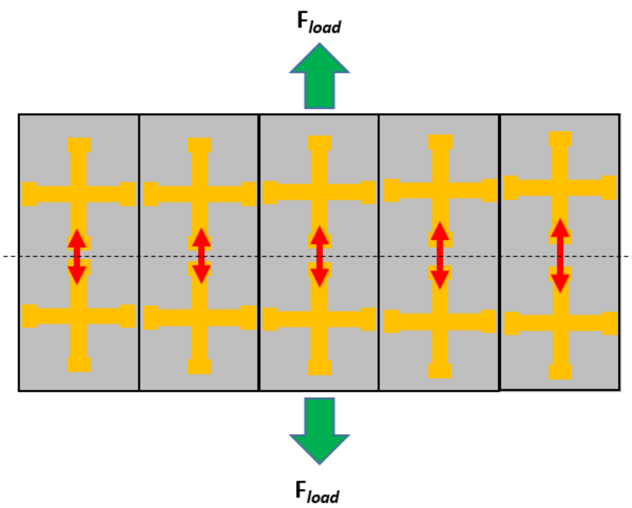


Figure 2: Schematic representation of the change in distance of the resonators during elongation under the effect of a tensile force F_{load}

Due to the increase of distance, the electromagnetic coupling decreases, resulting in a frequency shift of the resonant frequency of the resonator array. With the shift of the resonance frequency, the frequency of the anti-resonance also shifts, as depicted in Figure 3.

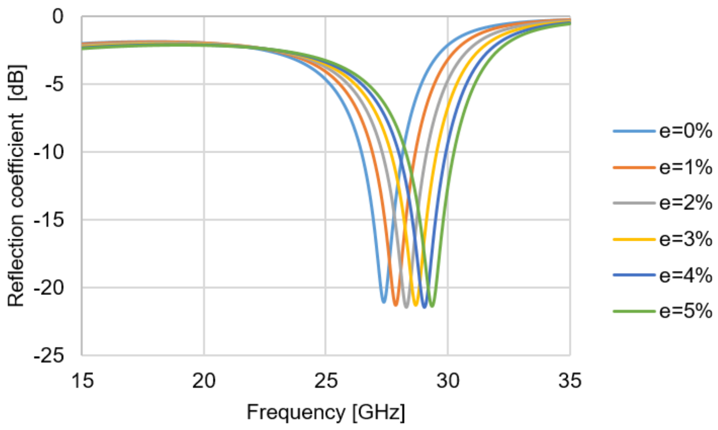
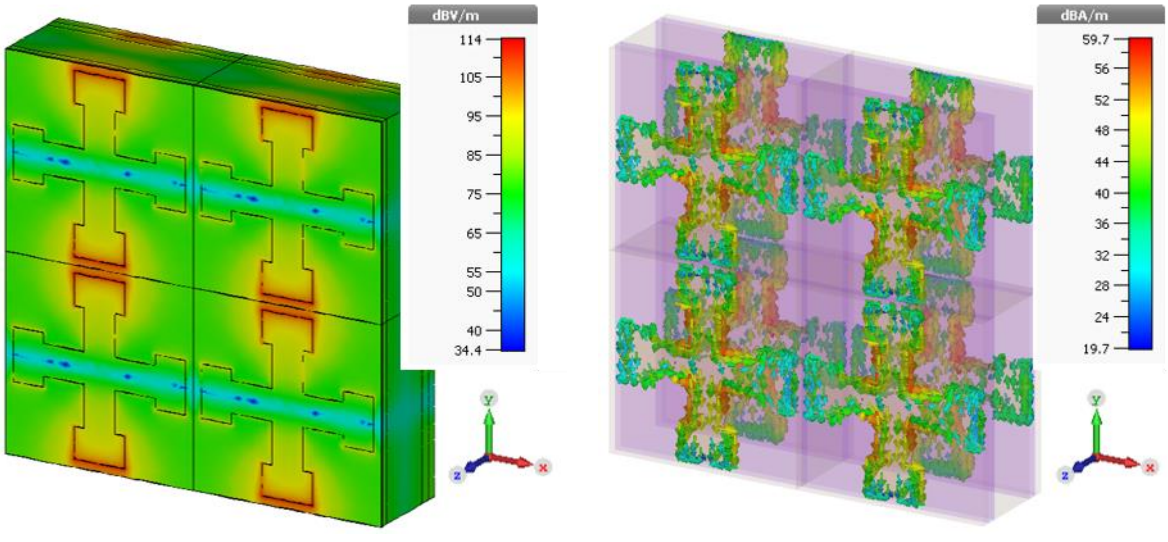


Figure 3: Simulation results of the numerically calculated reflection response causing an elongation of the unit cell between 0 and 5%

Figure 3 illustrates the calculated reflection response of the modelled and functionalised GFRP sample in the frequency range from 15 GHz to 35 GHz. The initial state without a lateral increase in distance of the resonators shows a reflection minimum at 27.38 GHz. The reflection minimum shifts to higher frequency when the distance between the resonators is increased. The default distance between two adjacent resonators is equal to 150 µm. This value results from the design rules of the printed circuit board (PCB) manufacturer. The numerical analysis of the elongation is carried out by enlarging the unit cell in the direction of the applied tensile force, whereby the size of the resonator remains the same. In the present case, the elongation is in the direction of the electric field vector of the incident electromagnetic wave. In the numerical simulation, an elongation in the range between 0% and 5% is considered. The observation of the electric field image (Figure 4a) at 27.38 GHz shows a field concentration in the gap between two adjacent resonators in the direction of the electric field vector. The closer the resonators are to each other, the higher the field concentration. As the distance increases, the electromagnetic coupling decreases and so does the field concentration of the electric field. As the electric field concentration decreases, the capacitive load is also reduced, resulting in a frequency shift to higher frequencies, as shown in Figure 3.



a) b)

Figure 4: Visualisation of the a) electric field and b) current distribution at 27.38 GHz

The thickness of the considered functionalised sample is 1.3 mm. This corresponds to about a quarter of the wavelength in the GRP material at 27.36 GHz and, when excited by an electromagnetic wave, leads to the formation of an asynchronous surface current (Figure 4b) with respect to the two resonator arrays resulting in the formation of an anti-resonance, as shown in Figure 4b.

2.3 Fabrication

For the integration process of the resonator arrays into the lightweight structure made of fibre-reinforced plastic (GFRP), the designed and numerically analysed JC resonator array was fabricated on a 100 µm flexible and thin film polyimide substrate by a printed circuit board manufacturer. Two layers of the manufactured JC resonator arrays were integrated into the GFRP laminate using vacuum infusion technology. Therefore, the two JC resonator array are inserted between stacked layers of plain woven glass fibre fabrics, each with a fibre orientation of 0° and 90° and a grammage of 163g/m². The two resonator arrays were placed between the first and the second layer as well as the penultimate and last layer, as shown in Figure 5. The layer structure was evacuated to consolidate the layer stack and subsequently infused with a thermoset plastic (type epoxy resin L with hardener GL 2, R&G Faserverbundwerkstoffe GmbH). The volume flow of the thermoset plastic is determined by the external air pressure. After curing, the resulting laminate consist of 7 layers with an expected overall thickness of approx. 1.3 mm.

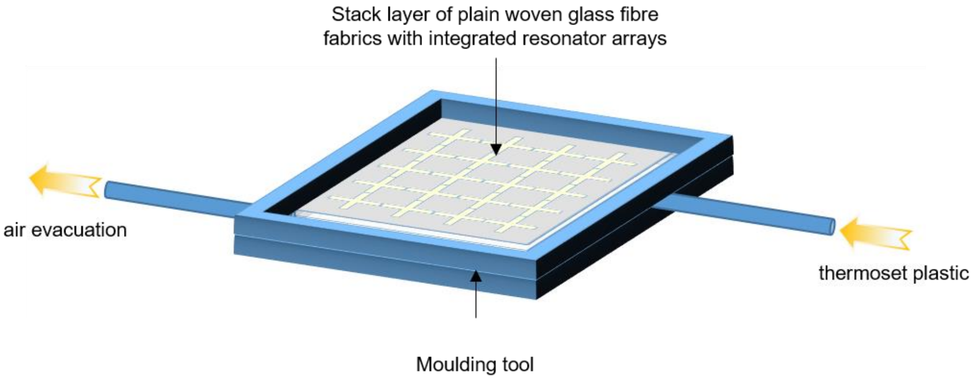


Figure 5: Schematic view of the fabrication process of a GFRP laminate with integrated resonator arrays using the vacuum infusion process

2.4 Experimental validation

The experimental validation of the investigated sensor approach was carried out by a reflection measurement using a vector network analyser (type ZVA50, Rohde & Schwarz) and two standard gain horn antennas (type Standard Gain Horn antennas 862, ARRA Inc.). The measurement was performed under mechanical load in the range of 0 kN and 30 kN using a tensile test machine (type TIRATEST 28100, Tira GmbH). After each incremental step of 2 kN, a reflection measurement was performed to evaluate the resonance behaviour of the loaded GFRP sample (Figure 6.). The test was terminated as soon as the GFRP laminate cracked due to the overload. Subsequently, the data of the reflection measurement was post-processed with Microsoft® Excel to analyse the resonance behaviour under load.

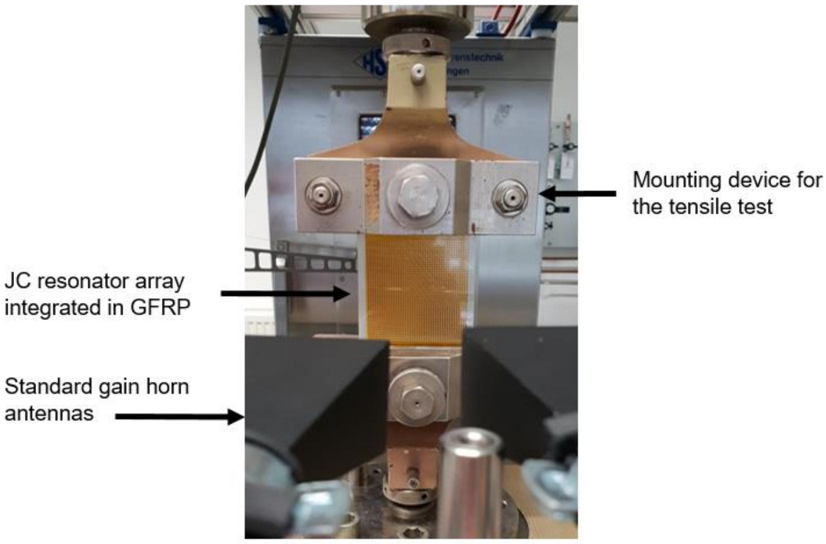
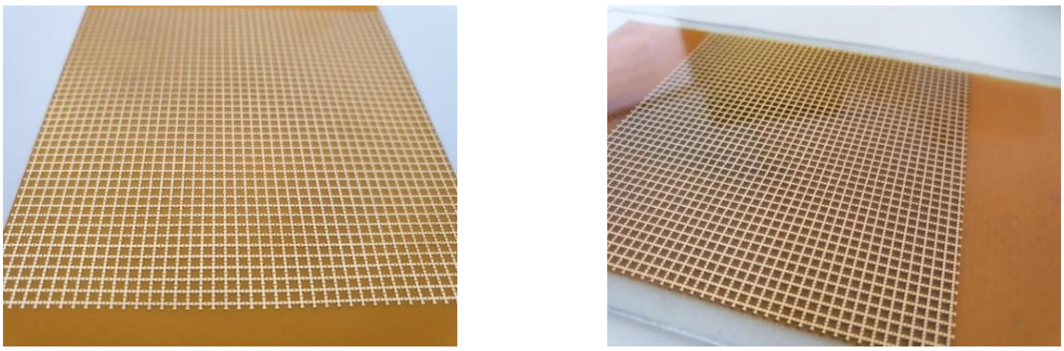


Figure 6: Measuring instrument used to monitor the resonance behaviour of the integrated JC resonator arrays during tensile tests

3 Results

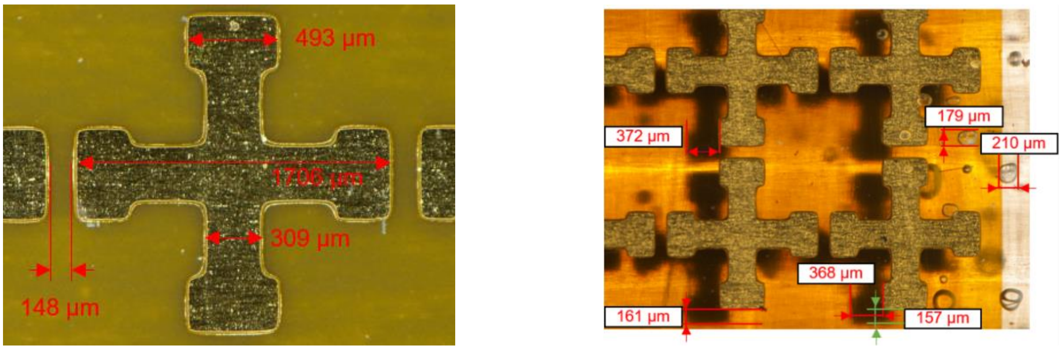
Figure 7a shows the manufactured JC resonator array on a flexible polyimide substrate of 100 µm thickness with 1849 single JC resonators building a two-dimensional sensitive surface. In Figure 7b the realised and functionalised GFRP laminate with a dimension of 80 mm x 160 mm and a thickness of about 1.3 mm is shown. The realised GFRP sample contains two integrated JC resonator arrays which are embedded close to the surface and separated by a layer stack of infused glass fibre fabrics, as described in section (2.3).



a) b)

Figure 7: The manufactured JC resonator array on a) a flexible polyimide substrate and the resonator array b) after the integration into GFRP material using the vacuum infusion process

The prepared samples were evaluated under a microscope after their manufacture, as shown in Figures 8a and 8b. In Figure 8a, the resonator was measured in order to compare it with the design specifications and thus determine deviations. In Figure 8b, the transmitted light was used to check whether the two resonator arrays were congruent. The microscope image clearly shows that the two resonator arrays not congruently superimposed but shifted relative to each other. This displacement results from the limited accuracy of the manual placement of the resonator arrays during the layer stacking for the vacuum infusion process.



a) b)

Figure 8: Microscopic image of the a) non-integrated resonator array and b) after integration into the polymer matrix (GFRP)

To validate the obtained numerical results with respect to the resonance behaviour, a reflection measurement was performed using two standard gain horn antennas and a vector network analyser (sec. 2.4) and the measured results were subsequently analysed and plotted using Microsoft® Excel. The plotted frequency-depended reflection coefficients that were recorded after increasing the elongation are visualised in Figure 9. The visualised curves were smoothed to reduce interference phenomena in the measurements due to the measurement environment and the resulting multiple reflections. For the data shown, over 40 measurement samples were averaged. The plot of the reflection measurement shows the reflection behaviour in the range from 27 GHz to 30 GHz. It is obvious that a reflection minimum is formed at about 28.5 GHz and shifts slightly to higher frequencies when the load on the sample increases due to the increase in tensile force. At the same time as the frequency shift, a reduction of the quality factor and a broadening of the reflection minimum occurs.

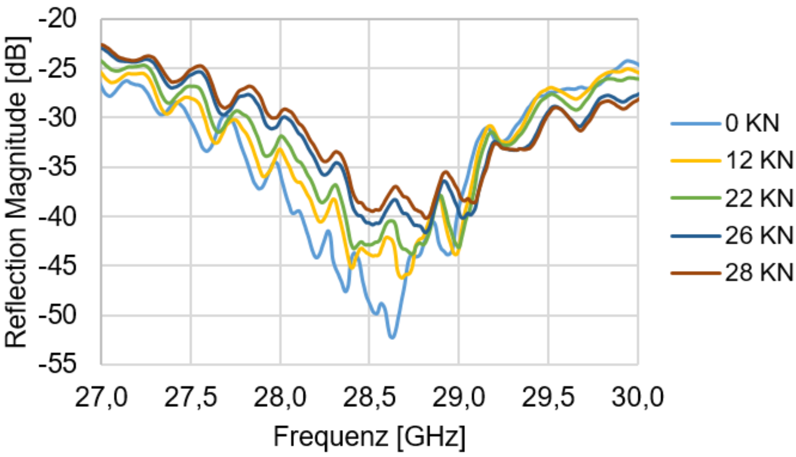


Figure 9: Measurement results of the performed tensile test

4 Discussion and conclusion

The obtained results show that it is possible to realise a resonator array with closely coupled JC resonators operating in the frequency range between 27 GHz and 30 GHz using PCB technology. Furthermore, it could be shown that flexible polyimide-based substrates with a structured copper cladding can be integrated into GFRP laminate to realise functionalised lightweight structures designed with an electromagnetic response. The comparison between numerical calculation and experimental validation shows similarities in the frequency behaviour of the functionalised GRP laminate, but also differences which did not occur in the numerical calculations and therefore need to be further analysed. Similar to the numerical results is the occurrence of a reflection minimum in the range between 25 GHz and 30 GHz as well as the direction of the frequency shift of the minimum when the tensile force is increased. However, the reflection measurement shows that the measured minimum is about 1 GHz above the result of the numerical simulation. This is explained on the one hand by the fact that the realised JC resonators are smaller in volume due to the manufacturing process and also look somewhat different in shape from those in the simulation model created (for example round corners, see Figure 8a). A post-simulation carried out with the real dimensions and curves of the resonator structure confirms this statement. On the other hand, there is an offset in the alignment of the two resonator arrays so that they are not congruently superimposed (see Figure 8b) and thus also affect the resonance behaviour. In addition, it must be considered that the distances between the integrated resonator arrays as well as the thickness of the fabricated GFRP laminate fluctuates due to in-homogeneities of the used materials and the applied integration technology and can therefore also influence the resonance response. The observation of the curve under load shows a shift to higher frequencies as predicted by the numerical results. However, the frequency shift is relatively small compared to the simulation, since the numerical simulation considers a maximum strain of 5 %. Therefore, a lower elongation of the GFRP laminate can be inferred from the low frequency change, which is typically 1% for GFRP. Furthermore, the measurement results show a reduction of the quality factor and a widening of the reflection minimum in case of growing tensile force applied to the GFRP laminate, thus preventing an exact determination of the resonance frequency of the anti-resonance (reflection dip). This behaviour is not shown by the performed simulation and needs to be further investigated. Especially the widening of the reflection minimum is still an open question and can have different origins (non-linear expansion behaviour, deformation of the resonators, and misalignment of the two resonator arrays). Due to the mentioned causes, different resonance frequencies can occur, which lead to an expansion of the reflection minimum due to the superposition of the individual resonance frequencies of the anti-resonances. In addition, it has been shown that the experimental validation is challenging due to the metallic environment. Because of the difficult measurement environment, additional reflections may occur which negatively influence the sensor signal (interferences). For this reason, a post-processing of the sensor data (e.g. by signal smoothing) is necessary in order to be able to carry out a signal evaluation.

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