Metasurface-Enhanced Antenna for Microwave Breast Imaging

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Abstract—In this paper, a hardware advancement for a microwave multi-static system for breast cancer detection is presented. In particular, we propose a metasurface-enhanced antenna capable of enhancing relevant “weak” signals backscattered by a tumour-mimicking target inserted in a breast phantom. Furthermore, we simulate a radar-based approach in CST Microwave Studio and use our previously developed Huygens principle-based algorithm to produce images of the target. Our results indicate that the proposed metasurface-enhanced antenna can improve target localization and decrease image artefacts.

Index Terms—metasurface-enhanced antennas, breast cancer, microwave imaging, Huygens principle-based algorithm.

I. INTRODUCTION

Breast cancer is the most common cancer in the UK population, with around 54,700 new cases diagnosed in 2017, and the most common cancer in women, globally [1]. This type of cancer occurs when cells in the breast tissue grow uncontrollably, forming a tumour, which can be seen through medical imaging or felt as a lump. In the last decades, significant research efforts in the diagnosis and treatment of breast cancer has helped in increasing the survival rates and declining the number of deaths associated with this disease. This outcome is largely due to earlier detection. Thus, primary prevention through regular screening procedures is crucial [2].

Nowadays, regular mammograms are tests commonly used for early breast cancer diagnosis due to the fact that sometimes they are capable of providing initial diagnostics up to three years before the tumour can be felt as a lump [3]. However, X-rays mammography has its limitations. First of all, it is painful and it exposes the patient to low radiations which can add up over time. Secondly, mammograms are not 100% accurate and it exposes the patient to low radiations which can add up over time. Secondly, mammograms are not 100% accurate and may cause psychological harm associated with false test results [4].

Microwave imaging (MWI) is a promising alternative method to X-rays mammography because it is non-invasive and harmless to humans. Furthermore, this imaging technology is low-cost and can lead to quick diagnosis. MWI uses the contrast among various tissues to detect malignant tumours, which are measured to have higher dielectric permittivity as compared with healthy breast tissue [5]. The tissue dielectric contrast can be estimated using radar-based or tomographic reconstruction algorithms that are applied to the acquired data [6]. Various setups have been considered for microwave breast’s measurements [7], [8], [9]. These can be distinguished in two main categories: robotic and multi-static systems. Robotic systems are generally easier to calibrate but presents an increased noise floor due to the mechanical movement of the antennas around the breast. Multi-static systems are very fast in terms of data acquisition time because they consist of large number of antennas which are positioned around the breast at fixed locations [10], [11]. The hardware configuration of multi-static systems can be differentiated according to various factors, such as the type of acquired signals, the patient positioning, the acquisition surface and the use of coupling media [12].

In this paper, we propose a hardware advancement for the multi-static system reported in [10]. In particular, we take advantage of metamaterial (MM) technology to lower the resonance (at a specific frequency) of a previous developed Vivaldi antenna for breast cancer detection [13], [14]. MMs are engineered materials with peculiar electromagnetic (EM) properties, which have shown a strong potential in several applications and can be used to fabricate high gain and directivity antennas with tailor-made radiation patterns [15], [16], [17]. At microwave frequencies, miniaturized MM-based antennas have been also optimized for breast cancer detection [18], [19].

The metasurface (MTS)-enhanced antenna presented in this paper is capable of enhancing the “weak” signals scattered by a tumour-mimicking target inserted into a breast phantom, which might be relevant to acquire high-quality reconstruction images. The remainder of the paper is structured as follows. Section II reviews the metasurface-enhanced antenna design, the multi-static system simulation setup and the algorithm. Section III presents and discusses our results, and finally, Section IV concludes the work.

II. MATERIALS AND METHODS

A. Metasurface-Enhanced Antenna Design

In this section, a MTS-enhanced version of the Vivaldi antenna shown in Fig. 1a is proposed. In particular, the frequency response of the original antenna has been improved at 5 GHz by introducing resonating structures on the front side of the antenna’s substrate, as shown in Fig. 1b. The
double-square split-ring resonator (DS-SRR) used for the new antenna’s design includes two PEC square loops (thickness = 0.3 mm) with a 0.5 mm gap capacitance. The gap between the external and the internal loops is 0.45 mm. First, the number of DS-SRRs and their position has been manually optimized to achieve a deep resonance at 5 GHz. Then, the dimensions of the metal wires of a single DS-SRR have been refined through CST Trust Region Framework algorithm by setting a minimum resonance at 5 GHz as a goal. To examine the performance of the new antenna, reflection coefficient, gain and directivity were calculated over the 1-6 GHz frequency range by using CST Microwave Studio for the original antenna and the MTS-enhanced antenna. As shown in Fig. 2, we obtain a deep resonance (-42 dB) at 5 GHz when the resonators are added to front side of the Vivaldi antenna. Fig. 3 shows that gain and directivity are also slightly improved in the 3.5-6 GHz frequency range.

B. Eight-Antenna System for Breast Cancer Imaging

To further investigate whether the MTS-enhanced antenna is capable of improving breast cancer detection, the multi-static system for microwave breast cancer imaging reported in [10] was modelled in CST Microwave Studio and eight MTS-enhanced antennas were integrated in the setup. Then, the EM wave propagation was studied for a breast phantom model including only average breast tissue ("no target" scenario) and in the presence of a tumour-like target inside the breast volume ("with target" scenario). For each system, the S-parameters were measured over the 1–6 GHz frequency range and the antennas’ reflection coefficients were obtained. In addition, the signal difference “with target–no target” (dB) was calculated at relevant frequencies, and images of the tumour-mimicking inclusion were reconstructed through our Huygens principle-based algorithm.

Fig. 4a shows the simulated setup and its dimensions. The system consists of a cylindrical 8-antenna array embedded into a solid dielectric platform consisting of two concentric cylinders. The outer cylinder is made of acrylic ($\epsilon = 2.53; \tan\delta = 0.0119$) and contains 8 radial slots where the antennas are positioned. The inner cylinder ($\epsilon = 3; \tan\delta = 0.0119$) is curved as a breast shaped cup and contains the breast phantom. This second cylinder has the mechanical function of sustaining...
the breast, eliminating measurement’s uncertainties due to movements and breast position. Furthermore, it improves the impedance matching between the antennas and the breast. Our homogeneous breast phantom is characterized by dielectric properties fixed at 3 GHz ($\epsilon = 30.81; \tan\delta = 0.19$). These properties were averaged between glandular tissue ($\epsilon = 56.40$) and fat ($\epsilon = 5.22$) [20]. The tumour-mimicking target ($\epsilon = 59; \sigma = 1.2 \, \text{S/m}$) consists of a 30 mm diameter sphere which was placed in front of antenna 5, as shown in Fig. 4b.

C. Huygens Principle-Based Algorithm

Our previously developed Huygens principle-based algorithm [21] has already shown promising results for different applications, including breast cancer detection [22], [23], [24]. This algorithm is capable of reconstructing images of a target in a background medium by measuring only the field on the external surface of the object of study. According to the Huygens principle method, the reconstructed 2D E-field at location $\rho$ within the object is:

$$E_{\text{HP}}(\rho, m, f) = \sum_{n=1}^{N} E_{nm}(f) G(k|\rho_n - \rho|)$$  \hspace{1cm} (1)

where $E_{nm}$ is the field received from transmitter $m$ at receiver $n$, $G(k|\rho_n - \rho|)$ is the Green function as defined in [21] and $k$ is the medium’s wave number at frequency $f$.

III. RESULTS

As shown in Fig. 5, our simulation results indicate that the reflection coefficient of the Vivaldi antennas is significantly reduced in the presence of the resonators. Furthermore, Fig. 6 shows that there is a slight improvement in transmission in the direction of the breast diameter, which is also the direction containing the tumour-mimicking target. Transmission between antenna 1 and antenna 2 is contrarily reduced, indicating that the coupling effects between two MTS-enhanced neighbouring antennas decrease in the presence of the resonators.

The signal difference “with target - no target” (dB) as a function of the receivers’ location is shown in Fig. 7. This difference is plotted in function of the receivers’ location, at 4.5 GHz and 5 GHz. Despite Fig. 7a shows that there are a few receiver’s locations at which the previous antenna design works better, the signal scattered by the target is overall enhanced (up to 25 dB) in the presence of the MTS-Enhanced antennas.

![Fig. 4. (a) Wire frame of the simulated setup with its dimensions and (b) tumour-mimicking target placed in front of antenna 5. The antennas are numbered clockwise starting from the antenna opposite to the target.](image)

![Fig. 5. Reflection coefficient for the “with target” configuration for (a) the 8-Vivaldi antenna array and (b) the 8-MTS-enhanced Vivaldi antenna array.](image)

![Fig. 6. (a) S51-Parameter for the “no target” configuration with (solid lines) and without DS-SRRs (dotted lines) and (b) S21-Parameter for the “no target” configuration with (solid lines) and without DS-SRRs (dotted lines).](image)
Fig. 7. Signal difference “with target - no target” (dB) as a function of the receivers’ location, plotted at (a) 4.5 GHz and (b) 5 GHz for the Vivaldi antenna-array (dotted lines) and the MTS-enhanced Vivaldi antenna-array (solid lines). The “weak” signal scattered from the target is overall enhanced by the new antennas.

Fig. 8. (a) Pre-normalised and (b) normalised images of the tumour-mimicking target reconstructed via our radar-based algorithm for the Vivaldi antenna-array. (c) Pre-normalised and (d) normalised images of the tumour-mimicking target for the MTS-enhanced antenna-array. The images are rotated by 90 degrees compared to Fig. 4b.

Images of the tumour-mimicking target reconstructed through our Huygens principle-based algorithm for the Vivaldi antenna-array and the MTS-enhanced antenna-array are shown in Fig. 8. These results clearly indicate that the proposed MTS-enhanced antenna enables a correct detection and localization of the target due to transmission enhancement and reduction of artefacts.

IV. CONCLUSION

In conclusion, the proposed MTS-enhanced antenna presents a reduced reflection coefficient and slightly increased gain and directivity. In addition, the results clearly indicate that the transmission through the breast phantom is enhanced (5 dB at 5 GHz) due to the presence of the resonators, whereas the coupling effects between two MTS-enhanced antennas are reduced. Moreover, the new antenna overall enhances the signals scattered from a tumour-mimicking target, which are particularly relevant to our near-field imaging application, as they may help in enabling target’s detection. Our ongoing work is focused on improving the proposed antenna design and carrying on experimental studies, to realistically assess the benefits from this approach.

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