Rectangular Patch Antenna on Split-ring Resonators Substrate for THz Brain Imaging: Modeling and Testing

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***Abstract*—Large biomolecules and proteins associated with brain functions and human diseases, as Alzheimer's disease, exhibit unique fingerprints in the THz spectrum. As a result, THz biomedical imaging with near-field probes is a promising solution for medical diagnosis and brain study. Ultimately, antennas with significantly enhanced performance are required for in-vivo THz biomedical applications. In this work, a THz rectangular patch antenna on a metamaterial substrate operating at 1 THz is presented. The metamaterial substrate based on split-ring resonators improves the antenna's gain and directivity. Finally, measurements at the microwave regime of a scaled version of the proposed antenna have been performed to experimentally verify the theoretically estimated metamaterial effect on the antenna performance.**

Index terms- terahertz radiation, bio-imaging, split ring resonators, metamaterials

I. INTRODUCTION

The last decade, researchers working on biomedical applications have focused on the terahertz frequency region which lies between the microwave and the infrared electromagnetic spectra, ranging approximately from 0.1 to 10 THz. The difficulties generating and detecting THz radiation with optical or electronic methods had resulted in its negligence for a long time. However, the recent progress realized in THz technology has enhanced the research of THz applications as imaging and sensing [1]-[4].

Terahertz radiation bears specific characteristics that render it very appealing for biomedicine and medical imaging [4]-[7]. The energy of a THz photon ranges from 0.4 to 41 milli-eVs, which is not enough to ionize biological molecules classifying THz radiation as "non-ionizing" [8]. Additionally, any thermal effects created by THz waves are negligible, considering that present THz systems use power levels of 1 μW. Therefore, THz radiation reasonably is characterized as harmless for biological samples and safe to be used in biomedical applications.

Many chemical substances provide distinct absorption characteristics in the THz spectral range. Intermolecular vibrations of large bio-molecules exhibit resonances at THz frequencies, which are directly related to their molecular structure. In other words, specific proteins have distinct THz "fingerprints" [9] and thus, THz sensors can detect these absorptions and identify the protein [10]. Moreover, THz waves are strongly absorbed by water due to hydrogen bonds. Consequently, any change in the water content of biological tissues, as blood concentration in cancerous cells [11], can be detected by THz radiation.

More specifically, THz technology has been shown to be potentially useful for understanding brain functions in various conditions by identifying various neurotransmitters important for brain activity. Recently, the mechanisms of bipolar disorder have been associated with changes in the balance of different excitatory and inhibitory neurotransmitters [12]. Real-time terahertz (THz) spectroscopy has been used to image diseased human brain tissue in order to probe misfolded proteins involved in neurodegenerative phenomena [13]. Also, recent findings suggest that THz spectroscopy may be possible to identify soft protein microstructures, which form from naturally occurring proteins involved in several human diseases, such as Alzheimer's disease [14].

In this paper, the recent advances of our research regarding an effective THz planar antenna are presented. The antenna is intended to operate as emitting component of a novel 2-D THz imaging system [9], that will be used for imaging and characterization of biosamples associated to brain functionality. In this context, herein, we focus on the design of a THz rectangular patch antenna with significant gain enhancement at 1 THz. The novelty of this work is to use left-handed metamaterials for the antenna's substrate. In a previous work [15], two different designs of metamaterial antennas have been presented, a rectangular and a bow-tie, where the metallic parts have been simulated as perfect conductors. The results have shown that the metamaterial substrate with a SRRs array improves the antenna's performance. However, at THz frequencies the conductivity of metals is significantly decreased and thus, it is necessary to take into account the conductor's losses.

Herein, the design of the rectangular one has been improved and the simulations are performed for actual metal patch with finite conductivity, measured at THz frequencies. Also, the effect the metamaterial has on the

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antenna's performance is validated by scale measurements at the microwave regime.

II. ANTENNA SETUP

The proposed THz antenna will be used to emit the generated radiation of the 2-D THz imaging system. The source will be able to create a narrow THz signal by photomixing two coherent CW (continuous wave) optical signals [9].

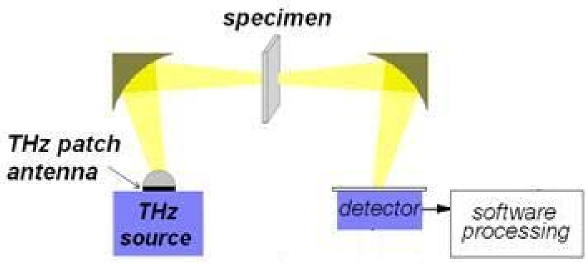

Fig. 1 Block diagram of the proposed THz imaging system.

Water molecules strongly absorb THz radiation and thus in-vivo biomedical applications demand antennas with significantly enhanced performance, as bio-tissues present high concentration in water. Specifically, planar antennas are commonly preferred for THz systems because they are robust and have low cost fabrication, using photolithography or electron-beam lithography. However, at THz frequencies planar antennas present power loss into substrate modes because of the thick substrates relatively to the terahertz wavelength [16] - [18].

A metamaterial based on split-ring resonators have been used for the antenna substrate in order to direct the radiation absorbed back to the desired radiation. The size of the split-ring resonators is of sub-wavelength dimensions [19]. V. G. Veselago firstly introduced left-handed metamaterials, which are artificial materials with negative refractive index [20]. A method to create negative refraction is by inducing metallic microstructures in a medium causing refraction and diffraction of the light propagating through that medium.

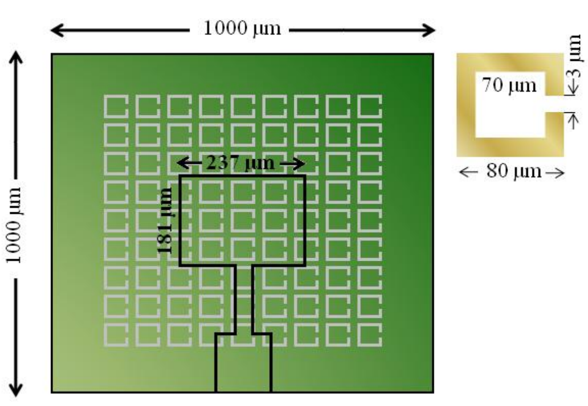

Fig. 2 Geometrical configuration of the THz rectangular patch antenna printed on a substrate with an array of metallic SRRs.

The radiation absorbed by the substrate creates oscillating currents and longitudinal plasmonic modes on the surface of the rings. The metamaterial substrate has been constructed by two layers of silicon with relative electrical permittivity $\varepsilon_r = 11.9$. On the lower layer of 40 µm thickness an array of 9x9 metallic SRRs is printed and on the upper layer of 30 µm the rectangular patch antenna is printed. The metallic parts of the antenna are considered gold with bulk conductivity σ_{bulk}=2.15x10^5 Ω^{-1}cm^{-1} [21]. The geometrical configurations of the THz antenna are shown in fig. 2.

III. SIMULATION RESULTS

The antenna design has been simulated using Ansoft HFSS. In order to exhibit the effect the metamaterial substrate has on the antenna's performance, the results have been compared to those of an antenna with equal dimensions but without a metamaterial substrate.

Figure 3 presents the radiation patterns of the rectangular patch antenna on metamaterial substrate (Fig. 3.a) with 4.83 dB gain and 10.66 dB directivity and of the reference antenna on a simple dielectric silicon substrate (Fig 3.b) with -1.07 dB gain and 2.47 dB directivity. At 1 THz, the SRRs metamaterial substrate clearly improves the antenna's performance, while the reflection co-efficient is decreased from -2.92 dB to -4.67 dB. Also, figure 4 shows the metamaterial antenna performs better than the simple one for most of the examined spectrum with exception a small area from 1003 to 1010 GHz.

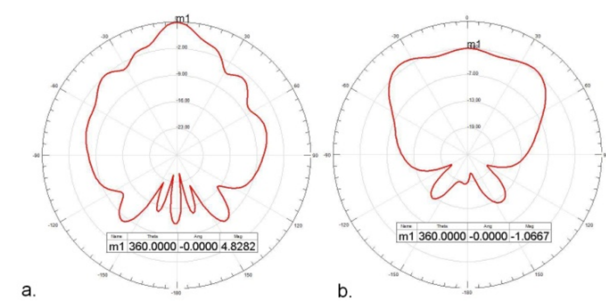

Fig. 3 Radiation pattern of rectangular patch antenna (a) on metamaterial substrate and (b) on simple dielectric substrate.

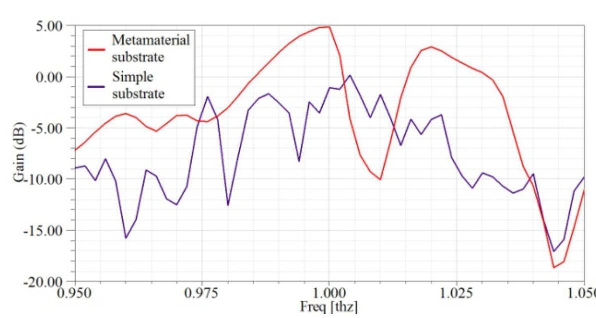

Fig. 4 Gain (dB) of the rectangular patch antenna on metamaterial substrate and on simple dielectric substrate over a 100 GHz bandwidth.

IV. EXPERIMENTAL RESULTS

The effect the metamaterial has on the antenna's performance has been validated by scale measurements of the designed antenna at the microwave regime. The rectangular patch antenna on SRRs metamaterial substrate has been redesigned 100 times larger in order to operate at 10 GHz. The metallic parts of the microwave antenna are made from copper. However, a material with a high electrical permittivity should be used for the substrate, as most dielectrics (i.e. silicon, GaAs) measured at THz frequencies present high permittivity values. For this reason, FR4 has been used, whose relative electrical permittivity is very difficult to predict at frequencies higher than 3-5 GHz, and it varies from 3.9 to 4.7 [22]. The constructed metamaterial antenna is shown in Fig. 5 (right). Also, figure 5 (left) shows a reference antenna with dimensions exactly equal to the metamaterial one, but without a SRRs array printed in the substrate.

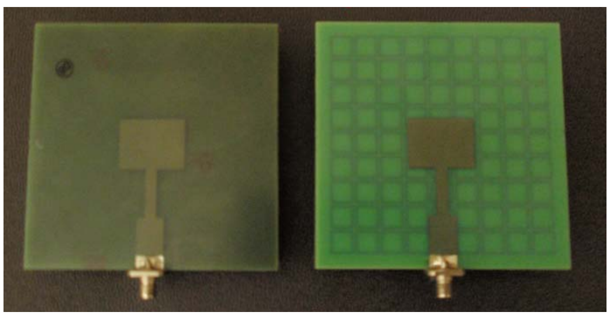

Fig. 5 Rectangular patch antenna on metamaterial substrate (right) and on simple dielectric substrate (left).

The measured reflection co-efficient for both the antennas over a bandwidth of 1.2 GHz is shown in fig. 6. The metamaterial antenna is resonating at 9.89 GHz with -12.38 dB reflection co-efficient, and respectively the antenna on a simple dielectric show a resonance at 9.883 GHz with -11.71 dB reflection co-efficient.

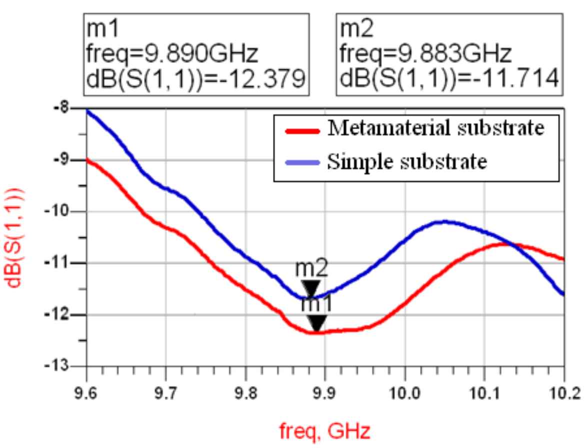

Fig. 6 Reflection co-efficient (dB) of the rectangular patch antenna on simple substrate and of the rectangular patch antenna on metamaterial substrate.

There is almost 1 dB improvement at the S_{11} measurements for most of the spectrum examined because of the metamaterial used for the antenna's substrate. The antenna's performance is enhanced by the presence of the SRRs array at 10GHz. This effect, based also on theory and previous simulation results, is expected to be more significant at THz frequencies, because of the thicker substrate and higher dielectric permittivity.

V. CONCLUSION

The proposed antenna design would operate as emitter of a novel 2-D THz imaging system [9]. That system would be used to create a database of brain tissue optical response at THz frequencies. The present work offers the possibility of identifying biomolecular markers, defining normal and abnormal concentrations of chemicals in brain and studying the interactions of brain proteins and their functions. Specifically, using the proposed setup ex-vivo measurements will be performed on prototype biological samples focusing into two main human diseases Alzheimer's disease and brain cancer. The measurements will possibly reveal anatomical and functional markers characterizing the diseases under study.

In this paper, an array of metallic split-ring resonators printed in a dielectric substrate is used to enhance the antenna's gain and directivity at 1 THz. The radiation absorbed by the substrate creates LC resonances on the rings, which, as a result, radiate back to the desired direction. The simulation results show significant improvement on the antenna's gain, almost 6 dB, and on its directivity, more than 8 dB. However, the proposed design is relatively narrowband, as the LC resonances depend on the size of the rings.

The proposed substrate could possibly operate efficiently under various types of antenna designs. More specifically, the combination of the SRRs array with a nonlinear crystal, i.e. GaAs GaP, is a promising solution for a THz photoconductive antenna substrate.

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