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Antennas on Metamaterial Substrates as Emitting Components for THz Biomedical Imaging

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Abstract—**Terahertz technology is considered a viable option for medical imaging, since many biological and chemical agents exhibit signatures in this spectral domain. Ultimately, large biomolecules and protein strands will be accessible, enabled by the coupling of THz science with near-field probes. In this paper, we present the recent advances of our research regarding a novel 2-D THz imaging system that it is intended to be used for imaging and characterization of tissue and biomolecule samples associated to brain functionality. Herein, we specifically focus on the emitting elements of the system, by studying two types of THz planar antennas for THz emission: a rectangular and a bow-tie patch antenna working at 1 THz. The aim and novelty of this work is to present an effective THz antenna with high gain and to this end we use left-handed materials for the substrate.**

Keywords —THz patch antenna; metamaterial; split-ring resonator.

I. INTRODUCTION

The last decade, there has been a raised interest in the THz regime by researchers working on biomedical applications. The THz spectrum includes frequencies from 0.1 to 10 THz and lies between the microwaves and infrared frequencies. This area of the electromagnetic spectrum was for a long time neglected because of its difficulties to approach it with optical or electronic methods. However, recent advances in THz generation and detection encouraged the research of THz applications, as THz spectroscopy, imaging and sensing.

Specific characteristics of this radiation render it very appealing to biomedicine and diagnostic medicine. A THz photon does not carry enough energy (0.4 - 41 milli-eVs) to ionize a biological molecule. In contrast to many popular techniques that use electromagnetic radiation to image biological tissues, T-rays have been characterized as “non-ionizing”. However, the thermal effects, which THz have on biomolecules, depend on the length of the exposure and on the power of the source [1].

Based on spectral specificity, most chemical substances exhibit specific absorption features in the THz range. Biomolecules naturally vibrate at terahertz frequencies, and each has a distinct terahertz "fingerprint" [2]. In other words, specific proteins absorb certain characteristic terahertz frequencies, which change their molecular arrangement, or conformation; sensors can then detect this absorption to characterize the protein.

In this context, THz technology may add significant knowledge to the understanding of brain function in health and disease by providing biochemical profiling of various neurotransmitters in various conditions. For example, recent findings suggest that a distress in the equilibrium of different excitatory and inhibitory neurotransmitters may be central to the mechanisms of bipolar disorder [3]. Recent findings support the abovementioned claims; in a novel study healthy and diseased snap-frozen tissue samples obtained from three regions of the human brain were distinguished using terahertz (THz) spectroscopy [3]. Real-time THz spectroscopy was used to detect biomolecule processes associated with neurodegenerative phenomena [4]. Also, recently it has been shown that terahertz (THz) spectroscopy can be used to differentiate soft protein microstructures which highly interest medical researchers, since they form from naturally occurring proteins suggested to be involved in several human diseases, such as Alzheimer’s disease [5].

In this paper, we present the recent advances of our research regarding a novel 2-D THz imaging system [2] that is intended to be used for imaging and characterization of tissue and biomolecule samples associated to brain functionality. Herein, we specifically focus on the emitting elements of the system, by studying two types of THz planar antennas for THz emission: a rectangular and a bow-tie patch antenna working at 1 THz. The aim and novelty of this work is to present an effective THz antenna with high gain and to this end we use left-handed materials for the substrate.

II. MATERIAL AND METHODS

A. System Description

The proposed 2-D THz imaging system (Fig. 1) will be capable of acquiring both the absorption and phase coefficients of the specimen within the frequency range 0.3-10 THz [6]. The experimental block diagram of the system is shown in Fig. 1. A laser source generating two coherent CW (continuous wave) optical signals drives an emitter that yields a THz beam at its output, through photomixing.

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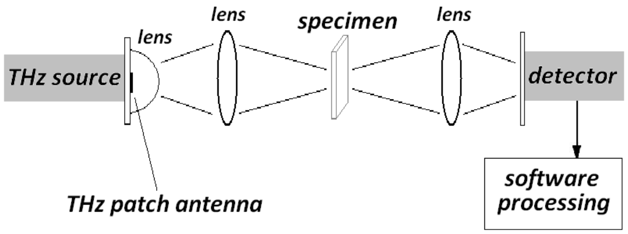

Figure 1. The proposed THz imaging system

The dual-CW laser source incorporated in the THz imaging system comprises a pulse-generating laser having its output spectrally broadened in a highly-nonlinear fiber so as to generate a supercontinuum. By inserting this signal into a cascade of filters like a Fabry-Perot and a band-pass filter or a suitable Fiber-Bragg grating, two spectral lines can be isolated prior to their mixing in the photoconductive dipole emitter. Frequency tuning of the resulting CW THz wave can be achieved by fine-tuning the laser repetition rate and/or replacing the output filters. In this way, generated narrowband THz radiation can be tuned within a broad THz frequency range spanning from 0.3-10 THz by altering the frequency spacing between the two optical CW signals.

In the present paper, we focus on studying an efficient emitting antenna for the 2-D THz imaging system (Fig. 1). Two types of patch antennas are presented to be used as components of the imaging system in order to efficiently guide the THz radiation to the biosample under investigation.

B. *Antenna Setups*

In THz transmission systems, the antenna holds an important role, especially, when it radiates in mediums with concentration of water molecules which absorb THz waves strongly. Thus, antennas with significant gain are required.

Planar antennas present some advantages that make them very appealing to THz researchers. These advantages are the robustness and the low cost fabrication, using photolithography or electron-beam lithography. The main hazard of the construction of THz patch antenna is the extremely thin substrate [7]. Consequently, the development of planar antennas for THz frequencies with thicker substrates is demanded. However, thick substrates cause significant power loss into substrate modes reducing the performance of the planar antenna. Photonic crystals have been used to propagate radiation from the substrate to free space [8]-[10]. The foreign objects inside the host material change the relative permittivity, ε_r, and the refractive index of the photonic crystal giving unique propagating characteristics [8]. Another technique to radiate back the power lost in the substrate is the use of multiple layers of different materials with different thicknesses as a substrate [11]. In higher frequencies, researchers use metal wire metamaterials in order to manipulate the substrate modes [12].

Left-handed metamaterials are artificial materials that present negative refraction, firstly introduced by V. G. Veselago [6], [13]. Negative refractive index is an electromagnetic property not observed in materials found in nature, but in microstructured materials constructed mainly by split-ring resonators [14]. Pendry et al. proposed to use SRRs with dimensions much smaller than the wavelength in order to diffract and refract light propagating through a medium [14]. An array of metallic elements printed on the antenna's substrate scatters back the electromagnetic waves. There have been experiments at the microwave spectrum [15] and more recently at the THz regime [16]. The oscillating currents on the rings cause LC-resonances and longitudal plasmon modes and as a result, the substrate to radiate back to free-space [16].

1) *Rectangular patch antenna:*

The first antenna design is a rectangular patch antenna 350x400 μm^2 printed on a two-layer substrate 1000x1000 μm^2. On the lower layer, which is 40 μm thick, the SRR array is printed and on the next layer, of 30 μm thickness, the patch antenna is printed. Fig. 2.a shows the geometrical configurations of the THz rectangular patch antenna. The antenna, the transmission line and the SRRs have been modeled as perfect conductors, while both layers of the substrate are dielectric with $\varepsilon_r = 11.9$.

The lower layer of the substrate is printed with a 9x9 array of metallic SRRs and as a result the substrate will behave as a metamaterial. The dimensions of the SRRs and their distance in the lattice are shown in Fig. 2.b. An important parameter is the relative position of each SRR on the substrate. For LC-resonances to be excited, the gap of a SRR has to be on the ring's side parallel to the exited electric field [18], [19]. So, for the given geometry the gaps are on the y-axis (Fig 2.a).

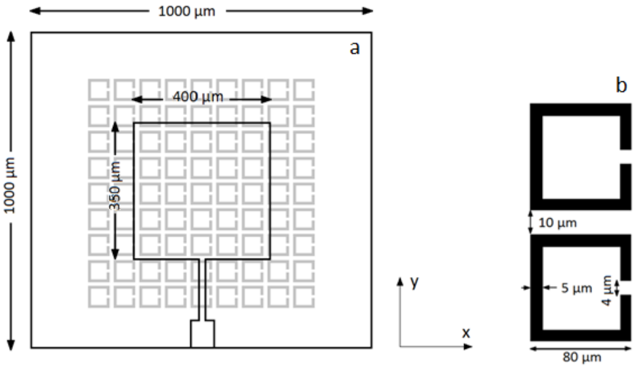

Figure 2. a. Geometrical configuration of the THz rectangular patch antenna printed on a substrate with an array of metallic SRRs b. Geometrical configurations of a SRR of the substrate and the distance between the SRRs in the lattice.

2) *Bow-tie patch antenna:*

The second antenna under examination is bow tie antenna, whose geometrical configurations are shown in Fig. 3. The antenna is printed on a rectangular two-layer substrate of a dielectric with ε_r=11.9. Both layers have thickness of 30 μm and the SRRs array is printed on the lower one. The array is constituted by 5x5 metallic elements –the dimensions of the SRRs in the array are shown in Fig. 3.b. Every metallic part is considered as perfect electric conductor.

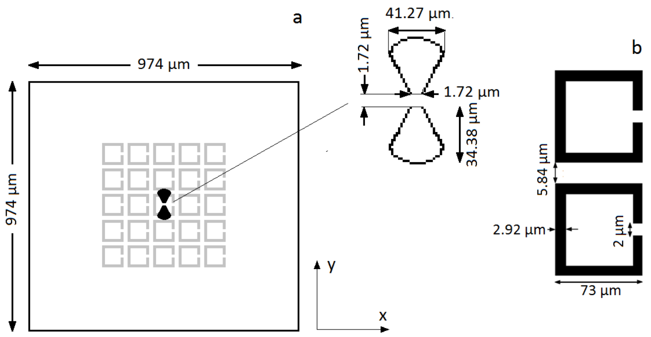

Figure 3. a. Geometrical configuration of the THz bow-tie patch antenna printed on a substrate with an array of metallic SRRs b. Geometrical configurations of a SRR of the substrate and the distance between the SRRs in the lattice.

III. SIMULATION RESULTS

The antenna designs have been simulated using Ansoft HFSS for 1 THz central operating frequency. For better understanding of the effect that the metamaterial substrate has on the antenna's performance, each antenna is compared to an antenna with the exactly same characteristics but without a metallic array printed on the substrate.

A. *Performance analysis of the rectangular patch antenna*

Figure 4.a shows the radiation pattern of the THz rectangular patch antenna over a metamaterial substrate constituting of a 9x9 SRRs array, while Fig. 4.b shows respectively the radiation pattern of the same antenna but with a simple dielectric substrate. The gain enhancement by using the metallic element array into the substrate is clear, as it is improved from -4.22 dB at the simple design to 8.82 dB.

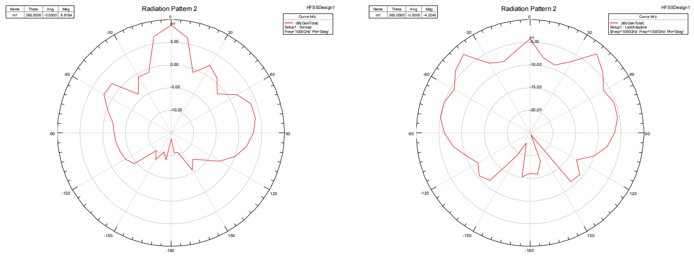

Figure 4. The radiation pattern of the rectangular patch antenna with a metamaterial substrate (on the left) and the radiation pattern of the reference antenna (on the right) at 1000GHz in dB.

The comparison of the two radiation patterns shows that the proposed antenna is much more directive. However, the rectangular patch antenna with the metamaterial substrate gives two secondary lobes at θ =80^{o} and at θ = -50^{o} and its radiation pattern presents an asymmetry which is caused by the relative alignment of the patch antenna and the SRRs on the substrate. The antenna presents a satisfying performance for a bandwidth of 16 GHz around the central frequency with gain larger than 4 dB.

B. *Performance analysis of the bow-tie patch antenna*

Respectively, Fig. 5 presents the radiation patterns of the bow-tie patch antenna with a metamaterial substrate and with a simple dielectric substrate.

The gain of the proposed antenna with the 5x5 array of metallic SRRs in the substrate is 12.92 dB, while the reference antenna gives 9.95 dB. It is very directive and without secondary lobes. Moreover, the bow-tie metamaterial antenna has a bandwidth of 50 GHz around the central frequency which is much larger than the one of rectangular patch antenna.

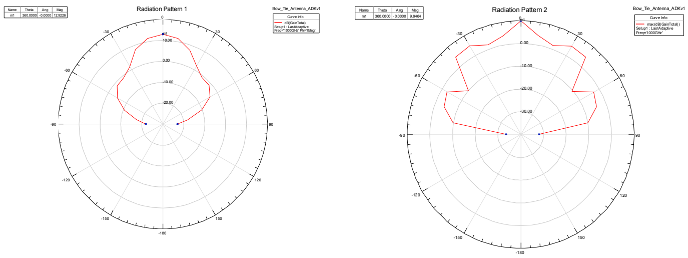

Figure 5. The radiation pattern of the bow-tie patch antenna with a metamaterial substrate (on the left) and the radiation pattern of the reference antenna (on the right) at 1000GHz in dB.

IV. DISCUSSION AND CONCLUSION

In the present paper two novel THz antennas to be used as emitting components of a THz bio-imaging system are presented. These antennas will be part of a novel 2-D THz imaging system that has been proposed in a previous work [2]. The positive performance effect that a metamaterial substrate with metallic elements has on the performance of a THz patch antenna is demonstrated. In all the cases that were examined significant gain enhancement was observed.

For many years, constructing such a design would present important difficulties. The microstructures printed on the silicon or GaAs layer demand 1 µm resolution. Recently, the development in e-beam lithography [20] and Dip Pen Nanolithography [21] made the printing with resolution of nanometers possible. Further improvement on the bandwidth would be possible by using more wideband antennas, as spiral or log-periodic patch antennas.

An imaging system such as the proposed one could possibly open new horizons towards the definition of biomolecular markers related to brain functionality and disease ex-vivo. Label-free measurement of protein-protein interactions is envisioned by scientists as cellular activity is taking place in live cells. Terahertz imaging offers the possibility of understanding complex reactions in real time chemical state changes of the samples under study.

An aim of the present research will be to identify different concentrations of chemicals in brain areas with an emphasis on neurotransmitter levels that relate to brain function and disease. More specifically, prototype biological samples of gradual biological complexity (i.e. single biomolecules, cultured cells, tissues) will be used. All samples will be associated to key aspects of brain physiology, including basic processes linked to anatomical and functional hallmarks of two major brain diseases (i.e. chronic neurodegeneration and brain cancer). Sample preparation procedures will be developed and tested in appropriate THz imaging platforms using various frequency ranges. It should be noted at this point that, one of the challenges in biosample measurements at THz frequencies is specimen preparation. Biomolecules are generally obtained as a liquid from tissue or body fluid. Analytical methods applicable to biomolecules in solution may be used, e.g. membrane method, in which the sample solution is dropped and dried on a polymer membrane filter before being used in terahertz spectroscopy measurements. In the case of fresh thin tissue samples which most closely mimic in vivo conditions, appropriate tissue handling because of high water content will be pursued (e.g. lyophilization (freeze drying)).

Future work will focus on using the proposed antennas in appropriate measurement setups using biological samples, as described above. Our future work also includes combination of brain imaging data from other methodologies (fMRI, EEG etc) with the THz spectroscopy data. Different methodologies allowing the assessment of multiple biophysical correlates of neural activation (blood flow, volume and oxygenation, conductivity and temperature) will enable detailed correlation studies that will further elucidate the nature of brain activation measurement and the neurovascular coupling. The accumulation of a wealth of brain functional data from molecular to system level will lead to a broad range of applications, spanning the delineation of brain networks, improved post-processing of the obtained measurements, understanding the basis of neuropsychiatric diseases and effective treatment design.

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