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Exploring PLA/Flax Substrates for Antenna Applications: Assessing Moisture, Temperature and Dielectric Constant Homogeneity

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Abstract—This paper investigates the potential of PLA/Flax substrates as eco-friendly alternatives for RF (Radio Frequency) antenna applications in the context of sustainability within the electronics industry. As electronic waste continues to mount globally and the use of RF-connected devices proliferates, there is a growing need for sustainable materials. This study explores the dielectric properties of PLA/Flax substrates and their implications for antenna design and performance. Our findings reveal promising RF performance, highlighting the viability of bio-sourced and biodegradable materials in RF engineering to address environmental concerns. Subsequent sections delve into the impact of moisture, and substrate homogeneity, offering valuable insights for sustainable RF systems.

Index Terms—Antennas, Biodegradable materials, Dielectric properties, Sustainability.

I. INTRODUCTION

The global electronics industry is facing a pressing challenge in the wake of depleting non-renewable resources and escalating concerns over anthropogenic climate change. The need for sustainable practices and materials has never been more evident, particularly in Europe, where public policies are shifting toward eco-friendly objectives. RF engineers are at the forefront of this transformation, tasked with developing RF systems that offer the same level of service while minimizing environmental impact, both in terms of carbon footprint and material consumption.

In response to this challenge, we have initiated an eco-design approach aimed at providing hardware and software tools, aligning with sustainability goals. This approach encompasses all stages of product development, including raw materials, manufacturing processes, transportation, packaging, usage, and end-of-life considerations. The overarching objective is to reduce environmental impacts across each stage by substituting conventional technologies with more environmentally friendly alternatives.

As a crucial initial step in this eco-design journey, we focus on benchmarking ecological PCB technologies for passive microwave circuits and comparing the performance of components manufactured using different substrates—

conventional and ecological. Our investigation centers on the use of a novel bio-sourced substrate made from polylactic acid (PLA) reinforced with flax fibers. This substrate is laminated with copper to create a double-sided PCB. Notably, it combines bio-sourced and biodegradable properties with compatibility for green electronics, featuring exceptional mechanical properties and a competitive strength-to-weight ratio compared to traditional glass fiber-reinforced polymers.

To illustrate the potential of this ecological substrate, we have developed many approaches, utilizing several substrates ranging from paper, glass, Rogers RO4003 and PLA/Flax. The RF performance exceeded that of current printed tags, highlighting the feasibility of sustainable end products that meet industry standards for performance and profitability [1]. However, the challenge persists, as connected objects currently account for only a fraction of the global carbon footprint. Although their individual impact is relatively low, the proliferation of these devices magnifies their overall environmental footprint. Therefore, a comprehensive evaluation of the environmental implications of various RF components, including substrates, becomes imperative.

Consider, for instance, the innovative realm of patch antennas, where breakthroughs in material science are ushering in a new era of possibilities. In one experiment [2], scientists created a patch antenna by infusing a cutting-edge organic silica aerogel nanoparticle derived from rice husk into a poly(butylene succinate) biomaterial. This ingenious combination led to a groundbreaking result. In a parallel endeavor [3], a patch antenna was crafted on a Polybutylene Succinate (PBA) substrate, showing great potential for deployment in wireless communication systems. Another exciting development came in the form of an Ultra-Wideband (UWB) Patch antenna [4], designed using sustainable jute as its substrate. The choice of jute, known for its durability and minimal environmental footprint, yielded remarkable outcomes.

These antennas represent just a glimpse of the captivating world of research at the intersection of materials science and communication technology. Beyond antennas, scientists have

ventured into the realm of PLA composite materials enriched with biodegradable components. This research [5] explores alternatives to traditional PCB materials, investigating assembly techniques and joint strength for conductive structures. Moreover, the scope extends to electronic systems, with a particular focus on implantable devices boasting wireless data and power transfer capabilities [6]. The overarching goal here is not only technological advancement but also environmental stewardship, aiming to reduce electronic and medical waste and, in turn, minimize our carbon footprint.

This paper delves into the RF characterization of the novel PLA/Flax substrate, the design and manufacture of a patch antenna on this substrate, and the measurement of antenna performance in terms of matching and radiation patterns. Additionally, we explore the influence of humidity on this antenna to assess its resilience in real-world conditions.

In the following sections, we will detail the RF characterization of the PLA/Flax substrate, the design and fabrication of patch antennas, and the measurement of antenna performance, with a particular focus on the effect of moisture.

II. LAMINATE PROPERTIES

A. Laminate fabrication

The substrates are manufactured with lamination and subtractive technology processes. Initially Flax fabric (woven, non-woven) and PLA is treated for Flame Retardancy (FR) with halogen free, environmental and health favorable, commercial agents (UL94-V0). To obtain uniform thickness, drying and ironing of FR and oil impregnated fabrics are performed with flat bed lamination technology with Reliant's Powerbond-HPC laminating method, where a high-pressure system is used to apply pressure during heating and cooling. The number of bio composite layers are optimized according to the required thickness of the PCB prepreg (aiming for ~1.6 mm as a standard). Then two layers of Cu are laminated (1 oz sheets) for final preparation of a double-sided PCB basis.

During the time, two generations of substrates were iterated, where the second batch had refined fiber structure to improve surface roughness and to improve finer copper surface. Also, for the second generation, bio-based, 100% organic oil was impregnated and solidified in controlled manner into the reinforcement fabric to eliminate the possibility fluids and moisture uptake to the fibers during PCB manufacturing and shelf life.

B. RF characterization

The success of any RF application heavily relies on a thorough understanding of the dielectric properties and loss characteristics of the substrate material. In this context, we embarked on a detailed RF characterization of the PLA/Flax substrates. It was carried out on two batches (2 successive generations described in previous paragraph), using, on the one hand, samples in the form of substrate freed from copper layers, and, on the other hand, a substrate with a double layer of copper, etched with a mechanical engraving machine from

LPKF to build a resonant microstrip line. Therefore, three distinct methods, the resonant cavity method (RCM), the free-space method (FS) and the resonant microstrip line (RML) were employed to characterize these novel bio-sourced substrates.

The RCM method involves measuring the resonant modes of a cavity perturbed by the insertion of a dielectric sample. By observing the changes in resonance frequency and quality factor of the modes caused by the inserted dielectric, we can iteratively calculate the complex permittivity of the material. Specifically, we focused on TE_{01p} modes, which remain relatively unaffected by the presence of the perturbing slot. This method is highly precise and allows for the determination of complex permittivity, thus dielectric constant (real permittivity) and loss tangent, at discrete frequencies. We have access to various cavities, enabling measurements at different frequencies ranging from 2.45 GHz to 90 GHz.

The FS method involves placing the sample to be characterized between two horn antennas equipped with focusing lenses. Reflection and transmission coefficients are measured using a vector network analyzer, and the dielectric parameters are extracted using appropriate algorithms. Like the RML method, FS method offers the advantage of covering a wide frequency range, spanning from 5 GHz to 110 GHz, making it suitable for a broad spectrum of RF applications. However, it is important to note that this method is most effective with planar samples and presents some limitations, such as singularities arising when the sample thickness is a multiple of half-wavelength at the operating frequency. These singularities can be mitigated through specific algorithms for dielectric materials.

Eventually, we used one of the generation #2 samples to build a thin resonant microstrip line on it. A microstrip line is resonant if its length equals half the guided wavelength or an integer multitude thereof, so it depends directly from the effective permittivity ϵ_{eff} of this planar structure because the guided wavelength is equal to the velocity of the electromagnetic wave divided by the frequency. For each measured resonant frequency, the real permittivity is thus easily deduced since, for such a thin line, $\epsilon_{eff} = (\epsilon_r + 1)/2$, the average of the dielectric and air contributions.

The measured real permittivity and loss tangent are shown in Table 1.

TABLE I. RF CHARACTERIZATION RESULTS

# Batch	Method	Frequency (GHz)	Loss tan	ϵ_r
1	RCM	0.93	0,05±0,01	2,49±0,17
1	RCM	2.48	0,04±0,01	2,3±0,16
1	FS	[50 - 70]	0,03±0,01	2,2±0,11
2	RML	[1.2-9.47]	NC	2,18±0,16

For both batches, the value of the real permittivity constant is lower than that of FR4, which brings some constraints to the design of matched impedance lines. This value can probably be explained by taking a three-component effective medium model: PLA [7], air and flax. However, the loss tangent

obtained is comparable to that of FR4 and should therefore pose no particular problem for the propagation of fast signals.

Our investigations yielded critical data regarding the real permittivity and loss tangent of the PLA/Flax substrate. These findings are essential for subsequent antenna design and simulation, as they form the foundation for accurate modeling of the electromagnetic behavior of the material.

III. ANTENNA DESIGN

With a comprehensive understanding of the PLA/Flax substrate's RF characteristics, we proceeded to design and manufacture a patch antenna for Wi-Fi applications in the IEEE 802.11ac standard, operating in the frequency range of 5.15 GHz to 5.35 GHz. The choice of antenna frequency range aligns with the ubiquitous nature of Wi-Fi communications.

The antenna design process involved selecting a real permittivity and loss tangent for the PLA/Flax material. We have chosen an average ϵ_r and $\tan \delta$ from different batches of PLA/Flax. This resulted in a real permittivity of 2.25 and a loss tangent of 0.04 at 5 GHz. These values were then incorporated into the CST simulation software to optimize the antenna design.

The patch antenna was configured as a rectangular patch with U-shaped slots and short-circuited stubs, and a U-shaped slot was added to enhance bandwidth. These modifications were optimized through simulations to achieve the desired performance characteristics. We also employed notches to control the S11 reflection coefficient and improve impedance matching. Following the design and fabrication of the PLA/Flax-based patch antenna (Fig. 1), we conducted extensive measurements to assess its performance. The first step involved measuring the reflection coefficient (S11) to evaluate antenna matching and impedance characteristics, as well as assessing the radiation patterns of the patch antenna, here presented at the operating frequency of 4.94 GHz (3).

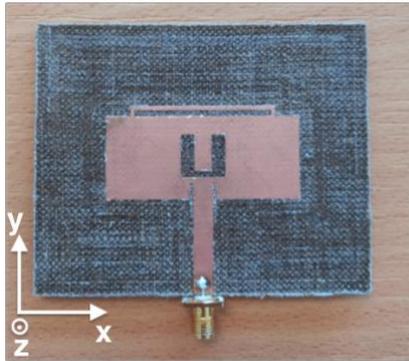


Fig. 1. PLA antenna, Substrate height = 1.6 mm

These results demonstrate the feasibility of using this ecological material for RF applications. Despite manufacturing challenges and substrate variations, the PLA/Flax-based antenna exhibited promising RF performance, highlighting the potential of bio-sourced and biodegradable materials in RF engineering while addressing environmental concerns. In the subsequent sections, we will delve into the effects of moisture on this antenna, providing

insights into their long-term stability and suitability for practical applications

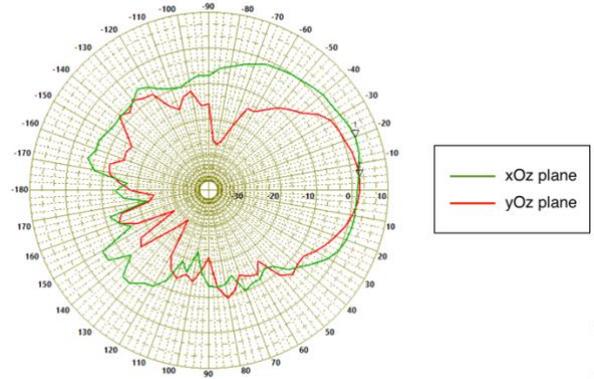


Fig. 2. Antenna radiation pattern.

IV. MOISTURE INFLUENCE ON ANTENNA MATCHING

On an uncoated biosourced and biodegradable substrate, one can expect some significant effects of moisture. These will affect the substrate dielectric characteristics and consequently the antenna characteristics. Moisture influence were evaluated on the manufactured patch antenna through resonance frequency characterization.

Moisture influence was characterized in a climate chamber. Its performance limitations led to setting the temperature to 40°C. On Fig. 3, the resonance frequency shift between 23,4%rH and 90%rH is marked. By sweeping moisture in both directions, we brought to light that the resonance frequency follows a hysteresis cycle in relation to moisture (Fig. 4). This result is in line with studies of moisture influence on cellulosic materials [8]: the resonance frequency is inversely proportional to the square root of the relative real permittivity. Therefore, the variation of the latter is given by:

$$\frac{\Delta \epsilon_R}{\epsilon_R} = 2 \frac{\Delta f}{f} \quad (1)$$

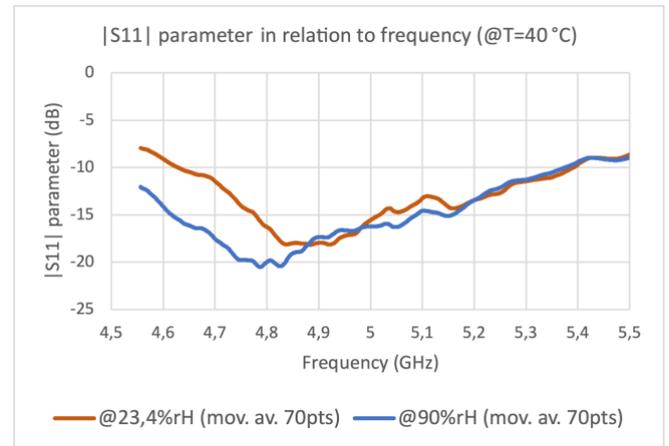


Fig. 3. Moisture influence on the resonance frequency

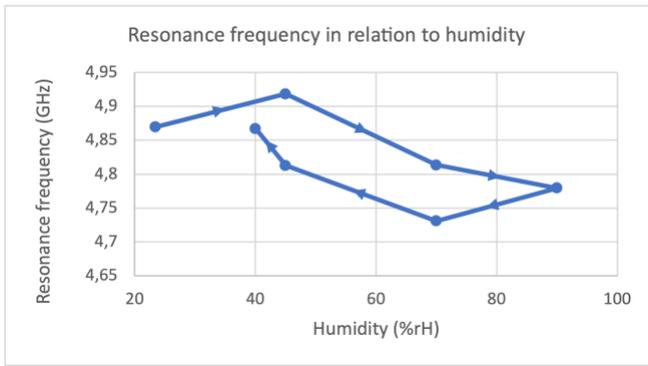


Fig. 4. Hysteresis phenomena (influence of moisture)

V. SUBSTRATE HOMOGENEITY STUDY

In order to complete the PLA/Flax investigation, we have extracted its relative real permittivity as a function of the position over the substrate, from 100 MHz up to 67GHz. To proceed, we set up a high frequency (HF) measurement and characterization technique described in reference [9] which uses a HF probe: 167 infinity GSG cascade probe with a pitch of 100 μ m. It is worthy nothing that the pitch is the distance between the center of the three metallic contact tips, Ground – Signal – Ground (GSG). The principle of the technique is based on two one-port microwave measurements. The first measurement is carried out with the HF probe raised in air (probe ‘up’). The second measurement is carried out by placing the HF probe directly on the PLA/Flax substrate (probe ‘down’). the measurement system (vector network analyzer - VNA, coaxial cable and HF probe) is calibrated using the LRRM technique which locates the reference plane of the measurement in the plane of the HF probe tips. The two measurements give access to S_{11} parameters (reflection coefficients referenced to 50 Ω) respectively due to the air and to the PLA/Flax. The S_{11} parameters lead to the determination of two admittances Y_{meas_UP} and Y_{meas_DOWN} from which we deduce the admittance Y_{AIR} and Y_{PLA} respectively due to the air and to the PLA/Flax. Knowing these admittances, in particular their difference, makes it possible to extract the complex permittivity of PLA/Flax substrate. Four different positions on the PLA were analyzed (Fig. 5), that is to say: the PLA/Flax relative real permittivity has been extracted for each position. Regarding the pitch of the HF probes, the PLA/Flax appears inhomogeneous.

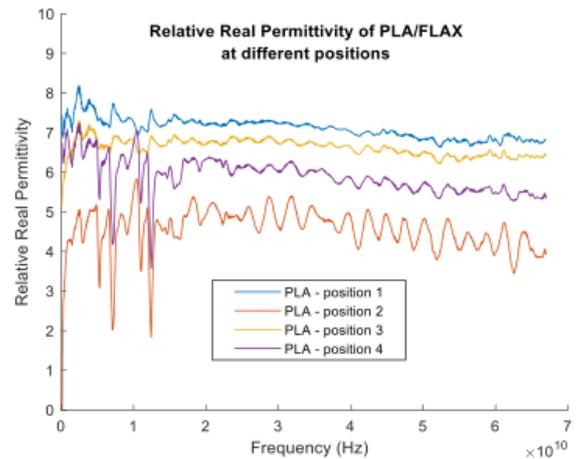


Fig. 5. Local measurements of relative real permittivity

Indeed, we can observe, in Fig. 5, that the extracted relative real permittivity shows different values according to the position on the substrate where it is evaluated. These results were already observed in reference [10], regarding the case of microelectronic packaging material called Molding resin. This behavior may impact propagated signals (for example, along interconnexions deposited on PLA/Flax) for frequencies whose waves length are at the same magnitude order of the inhomogeneous material area [11]. In Fig. 5, please notice that deviations appearing at the low frequency band (underneath 15 GHz) are due to a low frequency reference source problem of the VNA.

VI. CONCLUSION

In conclusion, this research underscores the urgency and promise of sustainable practices in the electronics industry. With depleting resources and escalating climate concerns, we stand at a critical juncture. Our eco-design approach, exemplified by the PLA/Flax substrate and innovative patch antenna, demonstrates that environmentally friendly alternatives can deliver performance while minimizing our carbon footprint.

Our study reveals that bio-sourced materials like PLA/Flax can play a pivotal role in RF engineering, offering both biodegradability and RF functionality. While challenges exist, such as manufacturing variations, our work shows that these materials hold great potential.

As we move forward, it is imperative to continue exploring eco-friendly materials, refining manufacturing processes, and expanding our understanding of their environmental impact. The path to sustainable electronics is one that requires innovation, collaboration, and a commitment to preserving our planet.

This research represents a step toward greener, more responsible technology development. By embracing sustainability in RF engineering, we can contribute to a more environmentally conscious future for the electronics industry.

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