RF Characterization of 3D Printed Flexible Materials - NinjaFlex Filaments

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Abstract— **The additive manufacturing technique of 3D printing has become increasingly popular for designs that have been previously unachievable due to cost and design complexity. Due to the special mechanical properties of NinjaFlex [1], there is great potential for its use in the 3D printed fabrications of numerous RF applications, such as strain sensors and wearable RF devices. This paper investigates for the first time the RF properties of various NinjaFlex filaments of varying densities utilizing the ring resonator approach, while these properties are verified on a 3D printed patch antenna topology.**

Index Terms — **3D printing, materiel characterization, UHF band, stretchable, patch antenna, NinjaFlex, flexible electronics, RF.**

I. Introduction

NinjaFlex filament, as one of the newest 3D printing materials in the market, was introduced by Fenner Drives, Inc. in 2014 [1]. It is one type of thermoplastic elastomers (TPEs) which are combinations of a thermoplastic and a rubber [2], potentially enabling 3D printing to be applied to numerous new areas, such as wearable RF electronics and antennas, due to its extremely high flexibility and stretchability. Shortly after its release, NinjaFlex was utilized on a wide variety of projects [3, 4]. Nevertheless, most of the projects have solely used NinjaFlex's mechanical properties. Even though it is a desirable material for 3D printed wearable electrical, bio-medical and flexible devices, there are, to the author's knowledge, no devices taking advantage of NinjaFlex's electrical properties, mostly due to the lack of electrical characterization of this material.

The additive manufacturing method of 3D printing offers unprecedented benefits, such as same day manufacturing of complex parts. Current 3D manufacturing technologies include fused deposition modeling (FDM), stereolithography (SL), and laser sintering [5]. While each one has advantages and disadvantages, FDM printing is the most prevalent, so much so that the technology has been used to create the first 3D printed parts in space [6]. While FDM printing has a large library of printable rigid thermoplastics that have been characterized for microwave designs [7], flexible thermoplastics are a new material for the field of 3D printing and as such have not been characterized.

FDM printing involves using filaments of materials wrapped on a spool that is then passed through a heated extruder to reach the glass transition temperature, generally around 190-280°C for thermoplastics, before being extruded into a pattern as designed by computer aided design (CAD) software, layer by layer. There are several proprietary solutions to printing flexible materials that require specific 3D printers [8]. Being limited to these expensive printers limits the options of materials to print in conjunction with the flexible substrate, thereby reducing design possibilities. With the RF characterization of a substrate available to anyone with a consumer grade 3D printer, microwave devices designed around the loss tangent ($tan\delta$) and the relative permittivity (ε_r) can be rapidly prototyped by any individual with additional filaments unavailable to industrial models. This opens up the door to a variety of possibilities, including individually fitted 3D printed flexible devices that may incorporate wireless components such as running position sensors, blood pressure meters, and other wearable devices.

A microstrip-fed ring resonator was chosen for the material characterization due to the size and accuracy requirements over the UHF band of interest [9]. A patch antenna was then used to demonstrate the feasibility and accuracy of the results of the characterization process.

The paper is divided into five sections. Section II describes the 3D printing process of the substrate. Section III contains the simulation and measured results of the ring resonators. Section IV details the design of the benchmarking patch antenna and compares it to experimental characterization results, while the last section covers the conclusions.

II. 3D Printing Process of NinjaFlex

Repeatable methods of fabrication of the substrate are necessary to create reliable results that can be verified. FDM printing has a variety of adjustable options that affect the final substrate properties. Important properties include layer height, amount of top and bottom solid layers, amount of perimeter walls, solid and infill patterns, and infill densities.

A substrate layer height of 100 microns is considered standard and is achievable from many consumer grade printers [10]. The amount of top and bottom layers both affects the mechanical strength of those sides; if there are not enough layers the top layer may become porous. An increase in the amount of perimeter walls increases the strength of the print, but one wall suffices to create a non-porous surface. Infill patterns are shown in Fig. 1. During testing, a Hilbert curve pattern is preferable for solid layers to create a non-porous bottom and top layer. As many printers by default print rectilinear, the rectilinear pattern was chosen for fabrication repeatability among different printer models [11]. The infill destiny can be varied, and the material is typically characterized for densities of 40%, 70%, and 100%, which can lead to varying mechanical properties.

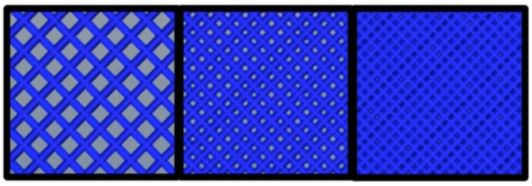

Fig. 1 Variety of infill rectilinear patterns available to print in slic3r. Left to Right: 40%, 70%, 100%.

The benchmarking patch antenna presented in this paper was fabricated on a 100% infill density substrate. All samples tested are made on the Hyrel System 30 3D printer, as shown in Fig. 2. This hardware uses a modified version of the Repetier controller software called Repetrel, which still uses the common slicing CAD software slic3r.

A. 3D Printing of Solid Substrate.

The first sheet of material to be characterized will be the 100% infill density. While a 100 micron print for all layers would be ideal, there can be issues with irregularities in the surface that is being 3D printed upon. For the first layer, a 200 micron layer print is chosen, which allows the print head to traverse over slightly uneven or irregular print beds without issues. Auto-leveling printers, such as the Printrbot, may be able to print more easily at a 100 micron first layer [10]. After the first solid 200 micron layer, another 100 micron solid layer is printed. For 100% density infill, layers identical to the bottom solid layers are printed. This results in 7 solid layers of 100 micron height where the infill would be. The final three top layers are solid one hundred micron layers. This results in 0.3 mm top and bottom solid surfaces, and 0.7 mm solid infill. This can be seen in Fig. 3. Three perimeter walls are used and should not affect the characterization of the material.

B. Creation of different density substrates.

Many of the same techniques are employed as the first solid substrate. The three top layers were chosen as the minimum amount to maintain a non-porous top layer at lower densities. Infill densities of 40% and 70% were printed. These numbers are chosen in order to almost completely span the printing range of the 3D printer while investigating significant differences in electromagnetic proprieties of these different substrates.

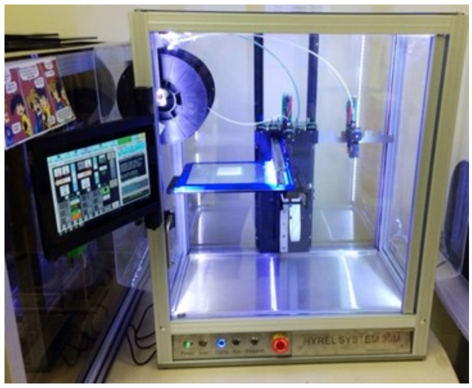

Fig. 2 Picture of Hyrel System 30 3D printer printing a 100% infill density 60×60 mm sample.

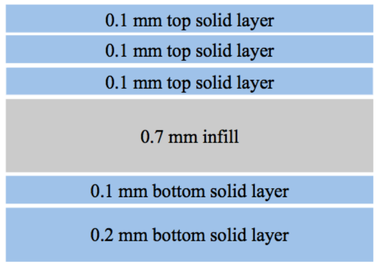

Fig. 3 Top/bottom solid layers and infill cross-sectional view.

III. RF CHARACTERIZATION OF NINJAFLEX FILAMENTS

A. Design of the ring-resonator.

From the microwave designer perspective, the most important characteristics of a new material are the dielectric permittivity and the loss tangent. Due to the lack of information regarding the electromagnetic properties of 3D printed substrates, including NinjaFlex, it is essential to derive this information in order to exploit this innovative material as a microwave substrate. Moreover, because typical 3D printers allow different values of density, a systematic process is mandatory to evaluate the electromagnetic characteristics of differently printed substrates.

Several techniques can be used to characterize a new material, in particular they can involve waveguide components, microwave resonators or coaxial probes [12]. The method adopted in this work is the ring-resonator technique, that is well known in literature and that has been used successfully for numerous non-standard materials [2,12].

This technique features the ability to determine the dielectric permittivity of the substrate from the analysis of the resonance frequencies of the ring, and the loss tangent from the evaluation of the quality factor of the resonant modes. Specifically, from the physical dimension (ring radius) and the resonance frequencies, it is possible to derive the effective relative dielectric permittivity as well as the dielectric permittivity under testing. In fact, this structure exhibits a resonant behavior every time that the length of the ring corresponds to an integer number of effective wavelengths.

The design of the ring-resonator is aided by a commercial full wave simulator. Two microstrip feeding lines are adopted to excite the ring and to collect the transmitted power. These feeding lines are separated by the resonator through 0.8 mm gaps. The width is set to achieve a characteristic impedance as close as possible to 50 Ohms by assuming a dielectric permittivity close to 3 and a substrate thickness of 1.20 mm. The gap is set intentionally large in order to more accurately get the loaded and unloaded quality factors of the resonator in case the transmitted power is very low and noisy measurements are expected. Moreover, this distance is also chosen to relax the constraints due to the process variations.

The design of the central part of this component, the ring, concerns mainly two dimensions: the radius and the width of the strip. The first one is set to achieve a resonant frequency as close as possible to 2.4 GHz. Starting from this point, the width of the ring strip has to be chosen in order to avoid higher modes [12] and to take into account the constraints of the manufacturing technique. As the ratio of the width and the summation of inner and outer radius has to be lower than 0.05, the chosen width is the maximum one that satisfies this relationship. The final design of the resonator is shown in Fig. 4.

B. Measurement and characterization results.

The ring structure is manufactured on three different substrates made of NinjaFlex of 40%, 70% and 100% densities. As the material has never been adopted for any electronics application, a proper manufacturing technique has been chosen. Since chemical etching involves acids the risk in damaging NinjaFlex through non-mechanical methods is very high. Inkjet printing is a possibility for characterization. The main issue concerns the porosity that a 3D printed material can exhibit and this deeply affects the layers of conductive ink. The last option is to employ a high precision milling machine, widely adopted for in-lab PCB realization. A 0.025 mm thick copper foil is stacked on the top of the substrate through a thin layer of epoxy glue. The glue epoxy solidifies allowing the milling machine to mill with additional precision. The electromagnetic characterization hereby proposed exploits not only the dielectric substrate but also considers the thin film of glue that is required to manufacture copper clad NinjaFlex.

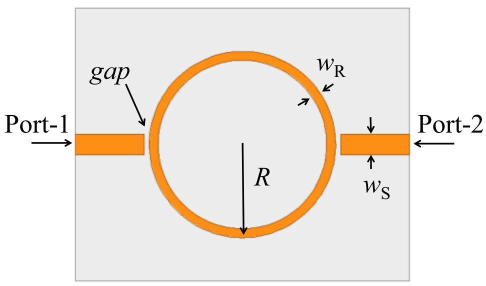

Fig. 4 Design of the ring resonator. The distance between Port-1 and Port-2 is 48.9 mm while the overall width of the substrate is 40 mm while. The other dimensions are wS=3 mm gap=0.8 mm R=13 mm wR=1.3 mm

The bottom is fully grounded through being covered with copper tape.

The measurement setup involves the R&S®ZVA8 vector network analyzer (VNA). The input and output feeding lines are connected to the VNA thanks to standard SMA-to-microstrip connectors fastened to the circuit with conductive epoxy glue. The ring resonator under test is shown in Fig. 5.

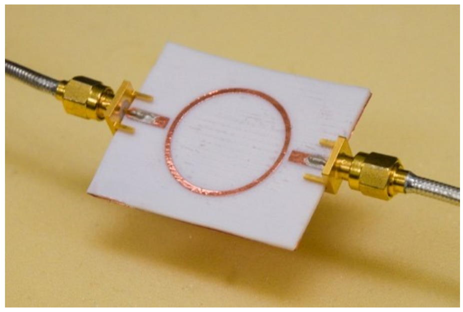

Fig. 5 The ring resonator realized on the 70% infill NinjaFlex.

Fig. 6 shows the frequency peaks for the three different densities. As expected, the higher infill densities lower the resonant frequency. This phenomenon is due to the high percentage of air in the substrate for low infill sample, that lowers the permittivity. Starting from these measurements the dielectric permittivity can be retrieved for each sample [9].

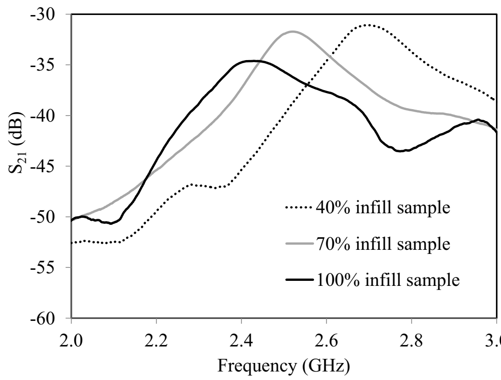

Fig. 6. Measurements of the transmission parameter of the three different ring resonators. The frequency shift due to different infill percentages can be noticed.

Fig. 7 shows the value of ε_r versus the infill percentage as well as the calculated loss tangent for the same substrates. The results show high losses compared to standard microwave substrates and as expected, the higher value of loss tangent is related to the sample with 100% of infill.

IV. Patch Antenna Experiment

When dealing with the characterization of a new material, an experimental validation is mandatory. The chosen benchmarking structure is a standard linear-polarized square patch antenna. Because the aim of this work is the characterization of NinjaFlex for wireless applications, the resonant frequency of the designed antenna is set at 2.4 GHz.

The antenna topology device includes a 50 Ohm microstrip feeding line to excite the patch and a coplanar transition to achieve the desired matching. The edge of the patch (w_{PATCH}) is optimized in order to exhibit a resonance at 2.4 GHz while the dimensions of the feeding line (width w_S, length l_S) are chosen to achieve a 50 Ohm impedance and to guarantee a minimum distance between the coaxial connector and the patch. In addition, a coplanar shaped transition (length l_T, width w_T) is designed to achieve the correct matching at 2.4 GHz.

Once the design is finalized, the antenna is manufactured with the same technique adopted for the ring resonator. The prototype is shown in Fig. 5 with the SMA-to-microstrip connector fastened with conductive epoxy glue.

This antenna has been validated through the measurement of the reflection coefficient values around the resonant frequency. The experimental setup is the same with the ring resonator measurements and involves a VNA for the calculation of the S_{11}. Fig. 9 shows the comparison of the simulation and the measurement results of the antenna.

The measured frequency is shifted down by approximately 60 MHz (around 2.5%) compared to the simulated value of 2.4 GHz. This kind of mismatch is probably due to manufacturing variability inherent of 3D printers that results in permittivity deviation with respect of the characterized sample.

The radiating behavior of the antenna is investigated through full wave analysis. The radiation efficiency is 20% by considering the characterized loss tangent and the copper finite conductivity while the maximum directivity is 4.19 dB.

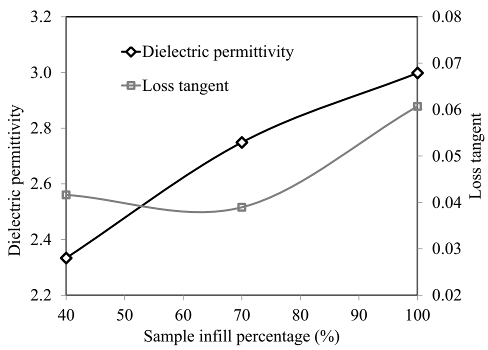

Fig. 7 Dielectric permittivity and loss tangent versus the infill percentage of the NinjaFlex sample.

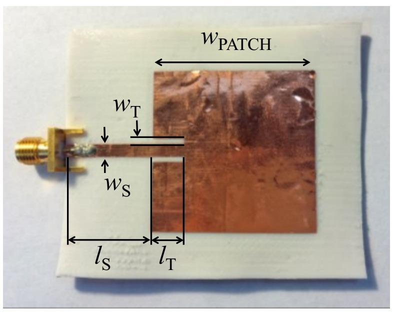

Fig. 8 The antenna benchmarking protoype manufactured on a 1.27 mm 100% infill density NinjaFlex substrate.

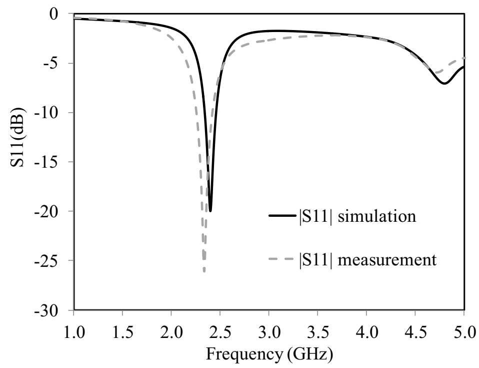

Fig.9. Superposition of the reflection coefficient simulated and measured of the realized patch antenna.

V. Conclusion

This paper presents for the first time the electrical properties of NinjaFlex, a commonly used flexible material for 3D printing processes, for applications around 2. The presented accurate electrical characteristics of various NinjaFlex filaments with different densities could enable for the first time the applications of 3D printing processes to a multitude of RF applications ranging from sensing to wireless communication and localization systems.

Acknowledgements

The author would like to thank the National Science Foundation with their Emerging Frontiers and Multidisciplinary Activities program, as well as the Defense Threat Reduction Agency for making research in this field possible.

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