This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2016.2516101, IEEE Antennas and Wireless Propagation Letters

Infill Dependent 3D-Printed Material Based on NinjaFlex Filament for Antenna Applications

Stefano Moscato, *Student Member, IEEE,* Ryan Bahr, *Student Member, IEEE*, Taoran Le, *Student Member, IEEE*, Marco Pasian, *Senior Member, IEEE*, Maurizio Bozzi, *Senior Member, IEEE*, Luca Perregrini, *Fellow, IEEE,* Manos M. Tentzeris, *Fellow, IEEE*

***Abstract*—This paper presents one of the first examples of the exploitation of 3D-printing in the fabrication of microwave components and antennas. Additive manufacturing represents an enabling technology for a wide range of electronic devices, thanks to its inherent features of fast prototyping, the reasonable accuracy, fully 3D topologies, and the low fabrication cost. A novel 3D printable flexible filament, based on NinjaFlex, has been adopted for manufacturing the substrate of a 3D printed patch antenna. NinjaFlex is a recently introduced material with extraordinary features in terms of mechanical strain, flexibility, and printability. Initially, the electrical properties of this material are investigated at 2.4 GHz using the ring resonator technique. The capability of selectively changing the dielectric constant by modifying the printed material density by fine tuning printing infill percentage is verified experimentally. Subsequently, a square patch antenna is prototyped through 3D printing and measured to validate the manufacturing technology. Finally, exploiting mechanical flexibility properties of NinjaFlex, the antenna is tested under different bending conditions.**

***Index Terms*—3D printing, flexible electronics, material characterization, NinjaFlex, patch antenna.**

I. Introduction

THE RECENT TRENDS in wireless sensor networks and the Internet of Things require the availability of low cost, compact and light weight, easy-to-integrate RF and microwave components and systems [1]. Moreover, applications in the field of wearable electronics, agriculture, and domotics have led to the investigation of novel materials and fabrication technologies. Textile materials have been adopted for the manufacturing of wearable components and antennas [2], plastic thin films have been proposed due to their flexibility [3], and paper has been adopted as an eco-friendly material [4]. Furthermore, an innovative flexible magnetic composite material has been adopted for wearable bio-sensors [5].

Besides the aforementioned materials, the emerging 3D-printing technology and the increasing commercial availability of printers and materials have opened new possibilities to RF and microwave designers [6]-[9]. The most interesting features of 3D printers are the manufacturing of complex 3D parts and the realization of arbitrary 3D shapes within bulky materials. Current 3D manufacturing technologies include fused deposition modeling (FDM), stereo-lithography (SL), and laser sintering [10]. In particular, the FDM technique is adopted in this work: it allows printing mainly plastic-based materials but cannot manage metallic deposition, due to the relative low temperatures (up to 280°C). The materials are heated and extruded into a two-dimensional pattern. The whole structure composed by 2D layers results into the final 3D printed structure. One unique feature of the 3D printing is the capability of changing the density of the printed object, by varying the infill percentage, from 100% to roughly 10% (depending on the printed material). This feature can be exploited to fabricate dielectric substrates with the desired permittivity, and this property can prove to be very attractive in the design of printed components and antennas. Moreover, this manufacturing process permits to tune "on demand" the mechanical properties of the material, achieving the desired lightweight and flexibility properties.

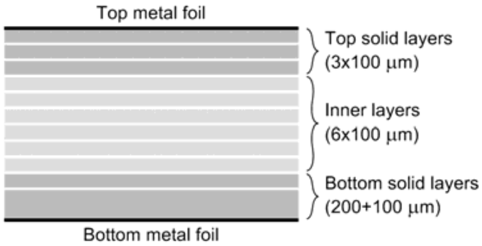
Among the large variety of available materials for 3D printing, the NinjaFlex filament is one of the newest, as it was introduced in 2014. It is part of the family of thermoplastic elastomers (TPEs) materials, which combine thermoplastic and rubber [11]. The result of this mixing is a material with extraordinary features in terms of mechanical strain, flexibility, and printability. The combination of 3D printing and flexible materials allows for the fast and easy manufacturing of bendable and conformal components and antennas [12]. Nevertheless, since this material was not originally intended for RF and microwave applications, its electrical parameters (namely, dielectric constant and loss tangent) need to be determined. Moreover, a technique needs to be developed for the metallization of the circuits, since it is not yet possible to print together NinjaFlex and high-conductivity materials.

This Letter presents for the first time the electrical characterization of NinjaFlex and its use in the implementation of a flexible patch antenna. The paper is organized as follows: Section II describes the printing procedure of the Ninjaflex-based substrate, and Section III highlights the possibility to obtain substrate materials with different dielectric permittivity values through the control of the infill percentage (preliminarily introduced in [13]), and presents the electromagnetic characterization results of some commonly used 3D printable materials up to the frequency of 2.4 GHz, based on the ring resonator technique. Finally, Section IV reports the design, manufacturing, and measurement of the patch antenna, and the characterization of its operation under different bending conditions.

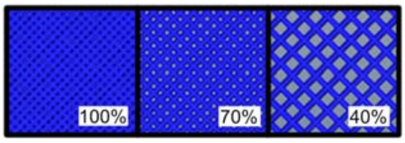
Manuscript received October 13, 2015; revised January 4, 2016; accepted January 6, 2016. This work has been supported by National Science Foundation (NSF) and Defense Threat Reduction Agency (DTRA).

S. Moscato, M. Pasian, M. Bozzi, and L. Perregrini are with the University of Pavia, Department of Electrical, Computer and Biomedical Engineering, Pavia, Italy (e-mail: ste.moscato@gmail.com, marco.pasian@unipv.it, maurizio.bozzi@unipv.it, luca.perregrini@unipv.it).

R. Bahr, T. Le, M. Tentzeris are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, USA (rbahr@gatech.edu, taoran3@gatech.edu, etentze@ece.gatech.edu).



(*a*)



(*b*)

Fig. 1 3D-printed NinjaFlex substrate: (*a*) stack of printed layers; (*b*) patterns with different infill percentage.

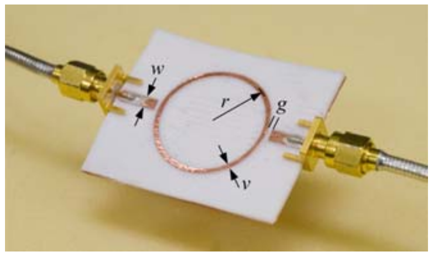


Fig. 2 Ring resonator for the characterization of 70% infill NinjaFlex substrate (dimensions in mm: r=13, v=1.3, w=3, g=0.8).

II. 3D Printing of NinjaFlex Substrate

The 3D printer used in this work is the Hyrel System 30: it is able to print a volume of 225x200x200 mm^3, with a planar resolution of 50 µm and a vertical resolution down to 20 µm. This printer exploits the FDM technology, works with any plastic materials (ABS, PLA, TPE, Nylon), and is particularly suitable for printing soft materials, such as NinjaFlex.

The FDM printing technique has a variety of adjustable options that affect the final substrate properties, both from the mechanical and the electromagnetic points of view. Important properties include extrusion speed and temperature, individual layer thickness/height, infill patterns and infill percentage. A proper combination of this large number of options needs to be identified, in order to achieve the desired material properties and a repeatable manufacturing process.

The individual layer height represents one of the most important features of 3D printers, which classifies the printers between consumer and professional. In particular, the layer height affects the resolution in the vertical dimension. A layer height of 100 µm is considered a standard value, and it can be achieved by most of the commercially available 3D printers. Several infill patterns can be adopted for the layers, including rectilinear, honeycomb and concentric. For any infill pattern, the infill percentage affects the density of the printed object and, consequently, its electrical properties (i.e., the dielectric permittivity) and mechanical stiffness.

The printed layers can be classified in external (top and bottom) layers and inner layers (Fig. 1*a*). The thickness of the external layers affects the overall mechanical stiffness. The external layers are always solid layers, with infill percentage of 100%. Moreover, the pattern adopted for the external layers is usually rectilinear, to avoid porosity and to reduce the surface roughness. On the other hand, the inner layers can be based on any infill patterns and infill percentage, and this affects the density of the printed object and its electrical properties. The substrate selected for the design of the 3D printed antenna prototype has an overall thickness of 1.20 mm and it is printed by stacking eleven layers. The bottom layer has a thickness of 200 µm and 100% filling. Its thickness is twice the thickness of the others layers, to achieve a strong adhesion on the printing bed. On top of this layer, another 100% filling layer is printed, to attain better mechanical stiffness. The six inner layers have a height of 100 µm/layer and can exhibit different infill percentage (ranging from 40% to 100%, Fig. 1*b*), to selectively modify the electromagnetic characteristics of the NinjaFlex substrate. The top of the stack consists of three solid layers (with 100% filling percentage): this final step is required to achieve better surface roughness of the substrate. The rectilinear pattern is employed for all layers, independently from the infill percentage, as it is the most reliable pattern even for low infill densities and permits a fast and easy fabrication process. The extrusion temperature was 235 °C and the print bed temperature was 40 °C. The printing speed was 10 mm/s for the boundary and 20 mm/s for the inner part.

Once the dielectric stack has been printed, a suitable technique is needed for the realization of metal strips and patches on the top and/or bottom faces of the substrate (Fig. 1). Inkjet printing is a possibility for the manufacturing of conductive traces, but the residual roughness and porosity of the printed dielectric material could affect the quality of the conductive traces. A possible alternative is based on attaching a copper foil on both faces of the substrate, which is subsequently patterned. The chemical etching does not appear suitable, as it involves the use of acids, that may damage the NinjaFlex material. A more attractive option is to employ a CNC milling machine, adopted in the classical PCB process.

In this work, a 25 µm thick copper foil was stacked on the top of the substrate by using a thin layer of epoxy glue. Once the epoxy is solidified, the desired pattern is obtained by milling machining. The bottom is fully grounded through standard copper tape, as there is no need for milling machining.

III. RF Characterization of NinjaFlex

As the fabrication of dielectric materials by additive techniques is a new topic in the field of microwave components and antennas, the use of the dielectric substrate obtained by 3D printing requires a preliminary electromagnetic characterization of its electrical properties, in terms of equivalent dielectric permittivity and loss tangent. The dielectric characteristics of the substrate largely depend on the used printed material, as well as the stack configuration and the height of the layers. In addition, the same material can exhibit different properties if printed with different settings.

Several techniques can be used to characterize dielectric materials, which include metallic waveguides, cavity resona-

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2016.2516101, IEEE Antennas and Wireless Propagation Letters

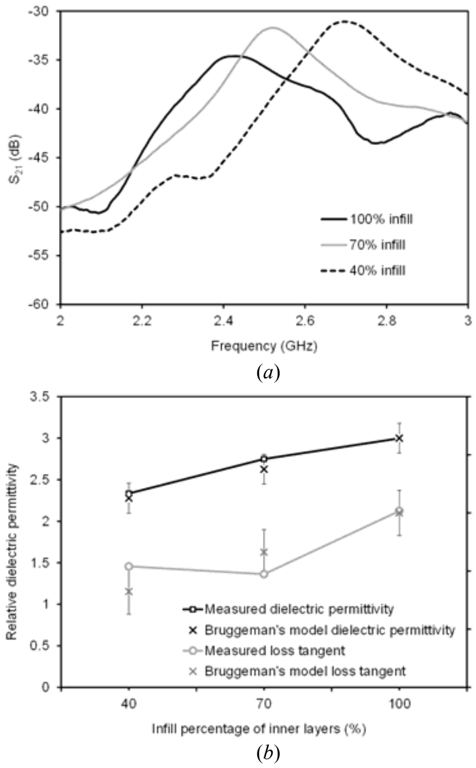


Fig. 3 Experimental characterization of NinjaFlex substrate: (*a*) measured transmission coefficient of three ring resonators on substrates with different infill; (*b*) relative dielectric permittivity and loss tangent versus the infill percentage of the NinjaFlex substrate.

tors, and coaxial probes [14]. The method adopted in this work is the ring-resonator technique, which has been widely and successfully adopted for numerous non-standard materials, including paper [15]. This technique permits to determine the effective 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 ring resonances.

The ring resonator was designed by using the commercial full-wave simulator Ansys HFSS (Fig. 2). The dimensions have been selected to achieve the first resonance at 2.4 GHz, for a substrate thickness of 1.2 mm and by assuming a dielectric permittivity of 3.0. The input/output feeding microstrip transmission lines has been chosen to achieve the characteristic impedance of 50 Ω. The dimension of the gaps between the input/output microstrip lines and the ring resonator was kept intentionally large, in order to obtain a loaded quality factor as close as possible to the unloaded one. All dimensions of the structure are given in the caption of Fig. 2.

Three different NinjaFlex 3D printed substrates have been characterized by using the ring-resonator technique, with infill percentage of 100%, 70% and 40%, respectively.

The measurement was performed by using an Anritsu 37347C vector network analyzer (VNA). The input and output feeding lines were connected to the VNA cables with standard SMA-to-microstrip transitions attached to the circuit with conductive epoxy glue. The prototype ring resonator with 70% infill percentage, together with the connectors and the VNA cables, are shown in Fig. 2.

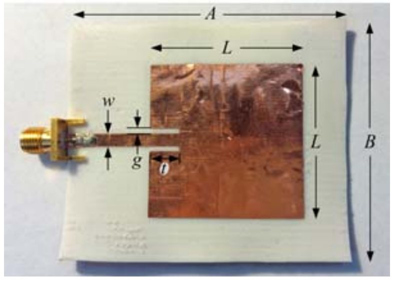


Fig. 4 Photograph of the square patch antenna on NinjaFlex substrate (dimensions in mm: A=65, B=55, L=35.8, w=3, g=1, t=7).

Fig. 3*a* shows the measured frequency response of the three ring resonators with different infill in the frequency band around the first resonance. As expected, a lower infill density leads to a higher resonant frequency. This phenomenon is due to the higher percentage of air in the substrate with lower infill density that decreases its effective dielectric permittivity. Based on these measurements, the values of permittivity and loss tangent have been retrieved for each sample [15]. Fig. 3*b* shows the resulting values of dielectric permittivity and loss tangent versus the infill percentage of the inner layers, compared to the theoretical values derived from the Bruggeman's model. Error bars shown in Fig. 3*b* were derived as in [15]. The results show that both permittivity and losses increase with infill percentage, due to the different balance between dielectric material and air. The printer was set to modify only the infill percentage of the inner layers, keeping the external layers nominally at 100% infill for all configurations.

IV. Implementation and Testing of the Antenna

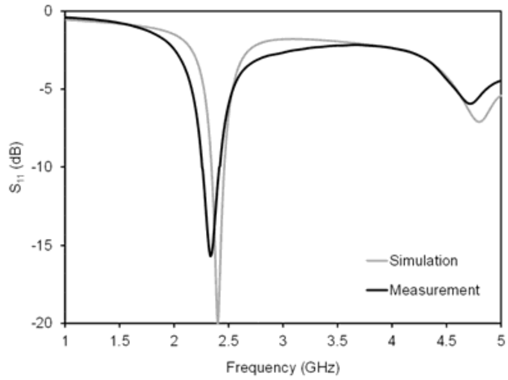
Based on the material characterization described above, a linearly polarized patch antenna has been designed and implemented on NinjaFlex substrate 100% infill. The stack of layers of Fig. 1 was used for printing the substrate.

The design of the antenna has been performed by using the full-wave simulator Ansys HFSS. The antenna dimensions have been optimized for operation frequency of 2.4 GHz, and the input microstrip line has been designed for a characteristic impedance of 50 Ω. The thickness of the substrate is 1.2 mm, the dielectric permittivity is 3.0 and the loss tangent 0.06.

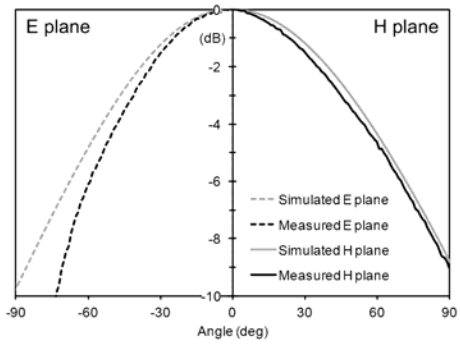
The antenna has been manufactured by adopting the technique described in Sec. II. A photograph of the prototype is shown in Fig. 4, together with all relevant dimensions of the antenna. The SMA-to-microstrip connector was attached to the microstrip line with a conductive epoxy glue.

The antenna performance has been assessed through the measurement of the input matching, the radiation pattern and the gain. The measurements have been performed by using an Anritsu 37347C VNA, and the radiation pattern and the gain were measured in an anechoic chamber.

The magnitude of the reflection coefficient is shown in Fig. 5*a*. The overall agreement between measurement and simulation is good over the entire frequency band from 1 GHz to 5 GHz. The measured resonance frequency is shifted down by 70 MHz with respect to the simulated one, corresponding to a shift of 3%. It could be attributed to printing variations due to inherent errors involved with most 3D-printers [16].



(*a*)



(*b*)

Fig. 5 Experimental characterization of the patch antenna on 100% infill NinjaFlex substrate: (*a*) reflection coefficient of the antenna; (*b*) radiation pattern of the antenna.

Moreover, Fig. 5*b* shows the comparison between the measured and the simulated radiation pattern of the antenna at the resonance frequency, in both the E and H planes. The agreement is good in the H plane, whereas the discrepancy in the E plane is attributed to the effect of measurement feeding cables. In addition, the measured maximum gain was –3.8 dB (compared to the simulated value of –2.9 dB), corresponding to an overall antenna efficiency of approximately 18%.

Finally, to exploit the flexibility of NinjaFlex substrate, the input matching of the antenna was also characterized under different bending conditions. To this aim, the antenna was placed on cylinders with different radius in order to bend the structure with a controlled curvature. Fig. 6 shows the measured reflection coefficient of the antenna under four different bending conditions. In all cases, the reflections coefficients are marginally affected by the curvature, with very slight shifts of the resonant frequency.

V. Conclusions

This Letter has presented the implementation of a patch antenna on NinjaFlex substrate, a new commercially available flexible material for 3D printing. After describing the fabrication process for the dielectric substrate with controlled permittivity and thickness through the modification of infill percentage, the characterization of three different substrates by using the ring-resonator technique has been reported. Finally, the design of a patch antenna at 2.4 GHz and its experimental

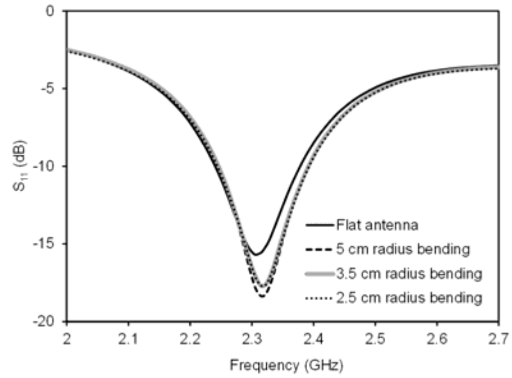


Fig. 6 Measured reflection coefficient of the flexible patch antenna under four different bending conditions.

verification under both nominal and bending conditions have been presented and discussed. This proposed 3D printing–based manufacturing technique paves the road to wearable applications and rapid prototyping of antennas on novel 3D printable flexible substrates with easily tunable and optimized electrical and mechanical characteristics.

References

[1] S.-H. Yang, *Wireless Sensor Networks: Principles, Design and Applications*, Springer, 2014.

[2] R. Moro *et al*., "Textile Microwave Components in Substrate Integrated Waveguide Technology," *IEEE Trans. Microwave Theory Techn.*, Vol. 63, No. 2, pp. 422-432, Feb. 2015.

[3] R. Moro *et al*., "Plastic-based Substrate Integrated Waveguide (SIW) components and antennas," *42nd European Microwave Conference* (EuMC 2012), Amsterdam, The Netherlands, Oct. 29-Nov. 1, 2012.

[4] R. Vyas *et al*., "Paper-Based RFID-Enabled Wireless Platforms for Sensing Applications," *IEEE Trans. Microwave Theory Techn.*, Vol. 57, No. 5, pp. 1370-1382, May 2009.

[5] L. Yang *et al*., "Conformal Magnetic Composite RFID for Wearable RF and Bio-Monitoring Applications," *IEEE Trans. Microwave Theory Techn.*, Vol. 56, No. 12, pp. 3223-3230, Dec. 2008.

[6] M. Ahmadloo and P. Mousavi, "A novel integrated dielectric-and-conductive ink 3D printing technique for fabrication of microwave devices," *2013 IEEE MTT-S International Microwave Symposium* (IMS2013), Seattle, WA, USA, June 2–7, 2013.

[7] P.I. Deffenbaugh, R.C. Rumpf, K.H. Church, "Broadband Microwave Frequency Characterization of 3-D Printed Materials," *IEEE Trans. Comp. Pack. Manuf. Techn.*, Vol. 3, No. 12, pp. 2147-2155, Dec. 2013.

[8] M. Liang *et al.*, "3D Printed Microwave Patch Antenna via Fused Deposition Method and Ultrasonic Wire Mesh Embedding Technique," *IEEE Antennas Wireless Propagat. Lett.*, Vol. 14, No. 1, pp. 1346-1349, 2015.

[9] J.G. Hester *et al*., "Additively Manufactured Nanotechnology and Origami-Enabled Flexible Microwave Electronics," *Proc. of IEEE*, Vol.103, No.4, pp.583-606, April 2015.

[10] C. Chua, K. Leong, and C. Lim, *Rapid Prototyping: Principles and Applications*. River Edge (NJ), USA, 2003.

[11] J. Hovath, *Mastering 3D Printing*. Apress Media, New York, 2014.

[12] B.-I. Wu, I. Ehrenberg, "Ultra conformal patch antenna array on a doubly curved surface," *IEEE Intern. Symp. Phased Array Systems & Technology*, pp.792-798, 15-18 Oct. 2013.

[13] T. Le *et al*. "A novel strain sensor based on 3D printing technology and 3D antenna design," *65th IEEE Electronic Components and Technology Conf.* (ECTC2015), pp. 981-986, San Diego, USA, May 26, 2015.

[14] L.-F. Chen *et al.*, *Microwave Electronics Measurement and Materials Characterization*. John Wiley & Sons, 2004.

[15] L. Yang, A. Rida, R. Vyas, M.M. Tentzeris, "RFID tag and RF structures on a paper substrate using inkjet-printing technology," *IEEE Trans. Microwave Theory Techn.*, Vol. 55, No. 12, pp. 2894–2901, Dec. 2007.

[16] D. A. Roberson, D. Espalin and R. B. Wicker, "3D printer selection: A decision-making evaluation and ranking model," *Virtual and Physical Prototyping*, Vol. 8, No. 3, pp. 201-212, 2013.