# UWB Antenna on 3D Printed Flexible Substrate and Foot Phantom

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***Abstract*—An ultra-wideband (UWB) monopole antenna on an additive manufactured (AM) flexible substrate for foot wear application is proposed. The 3D printing of foot phantoms for the testing of this type of antennas is also introduced. Inexpensive fuse filament fabrication (FFF) technology is utilized for these developments. Flexible polylactic acid plastic filament (PLA) material is used for the antenna while transparent PLA for the phantom. The antenna is intended for integration into the footwear tongue. The UWB monopole antenna achieves -10dB input impedance matching from 3.1GHz to over 10.6GHz in free-space, on the foot phantom and on the real human body. Simulation and measurement confirm the ultra-wideband operation of the antenna.**

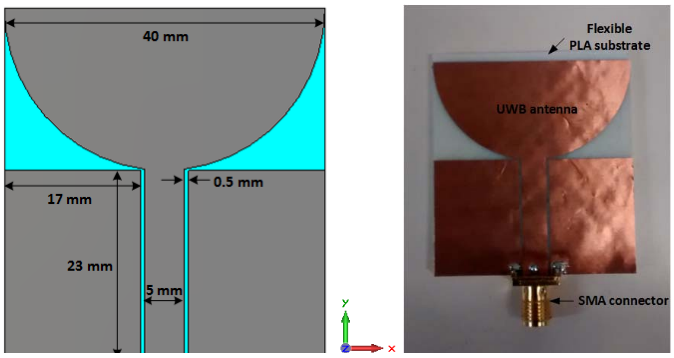
***Index Terms*—3D printing, Additive manufacturing, wearable antenna, foot wear.**

## I. Introduction

Wireless health monitoring has attracted significant attention in recent year. Monitoring of health is usually carried out through wearable sensors, wireless devices and a computer system. Wearable sensors receive the human body information, wireless devices provide communications and a computer system, or smart phone, provide data processing and storage [1]. Wearable antennas are needed for these systems [2] – [9]. Real time health monitoring can now be achieved, allowing for sensing and recording human body changes using body area networks.

Electronic footwear technology can enable the sensing of various human body parameters such as heartbeat, temperature, blood pressure and sweat emission. Ultra-wideband (UWB) technology suits the propagation range in body area networks for footwear application [6]. Planar UWB Antennas on footwear have been proposed and the corresponding body channels have been studied [6], [7]. This was carried out using rigid FR4 substrates, which limits the applicability of the studies. More recently, inkjet printing technology has been used to fabricate a flexible textile antenna [8].

Additive manufacturing or 3D printing is a technology that enables the fabrication of complex structures from a digital model. This can improve the integrated functionality of 3D structures through design flexibility. It also allows for fabrication using different types of materials. One of the most popular and least expensive 3DP techniques is fuse filament fabrication (FFF). Common materials that are used with FFF are polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). Standard PLA has been proved to be suitable for wearable antenna applications in [9]. There, a WLAN antenna was placed on a 3D printed bracelet.




(a) (b)

Fig. 1. UWB antenna on flexible PLA substrate: (a) dimensions of the antenna, (b) photograph of the antenna with the feed connector.

Human body phantoms are typically made using liquids (e.g sugar and saline solutions, alcohol), gels (e.g. polyethylene powder, glycerol), soft materials (Agar, silicon rubbers), and solids (eg. ceramics, resins). Discussions of these phantoms as well as on the permittivity and conductivity of the homogeneous tissue equivalent dielectric liquid were reported in [10]. In [9], 3D printing was used to replicate the outer layer of a human hand which was then filled with a sugar and saline solution.

This paper presents the use of inexpensive 3D printing technology for the development of flexible antennas and phantoms for foot wear applications. A UWB antenna is placed on a 3D printed flexible substrate and tested on an also printed foot phantom. The printed structures are fabricated using FFF technology. Low-cost PLA materials are employed for both developments. The antenna is tested on the foot's bridge and is intended for integration in the tongue of footwear. Studies on this specific location were not reported in [6] - [8]. The 3D printed phantom is filled with Indexsar liquid that replicates the inner human body tissues over a wide frequency range [11]. CST Microwave Studio™ was used for all simulations in this paper.

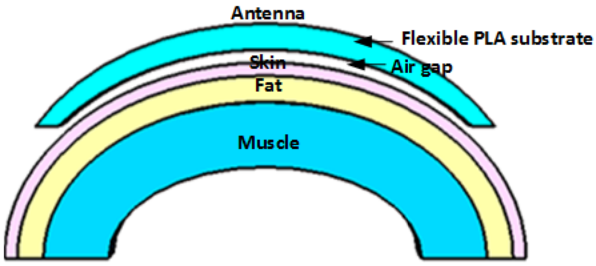



Fig. 2. Configuration of the UWB antenna shaped around the flexible substate and placed on a curved human tissue model

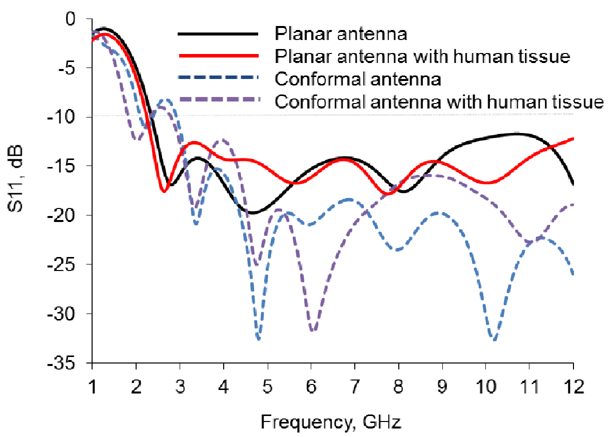



Fig. 3. Simulated reflection coefficient ($S_{11}$) of the planar and conformal UWB antennas with the human tissue model in free space

## II. FOOTWEAR ANTENNA ON FLEXIBLE 3D PRINTED SUBSTRATE

### *A. UWB Antenna Design*

Fig. 1(a) shows the geometry of the UWB antenna conformed on the substrate. The antenna is based on the wideband planar monopole concept and is fed by a coplanar waveguide transmission line [12]. The target frequency range for the antenna in free space is 3.1 - 10.6 GHz. The radius of the half circle of the antenna is a critical parameter in order to obtain UWB frequency operation with the suitable impedance matching. The antenna was designed for use with flexible PLA substrate having a dielectric constant of approximately 2.5 and thickness of 1.5 mm. The dielectric constant of the flexible PLA material was determined by the transmission coefficient of a thin dielectric slab of thickness (3mm) in a rectangular waveguide. Fig.1 (b) shows a photograph of the antenna on the flexible substrate.

As part of the simulation studies, the UWB antenna was shaped around a cylindrical form of radius of 11.25 mm and placed at distance of 1 mm from a human tissue model (Fig.2). The airgap between the antenna and the human tissue model is an important parameter, which affects the antenna performances such as the reflection coefficient and radiation characteristic.

The human model consisted of three layers (skin, fat and muscle) with the thicknesses of 1mm, 2mm and 5mm respectively. Their properties were extracted from Voxel Family of the CST Microwave Studio™. The overall dimension of the human model were approximately 46 mm × 45 mm × 8 mm. An additional polyester substrate of thickness of 0.05mm was attached to the flexible PLA layer.

The effect on the reflection coefficient ($S_{11}$) of shaping the planar antenna on a curved human tissue model is shown in Fig.3. As can be seen from the figure, the antenna is designed to offer better matching when curved. The antenna covers the UWB band (3.1 - 10.6 GHz) for all the cases studied with resonant modes shifting to a lower frequency in the presence of the human body. This shift is caused by the increase in the effective dielectric permittivity.

### *B. Antenna and foot phantom fabrication*

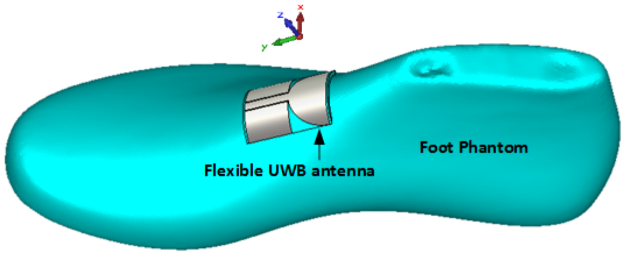
The Ultimaker 2 printer was used for the fabrication of the flexible substrate and the foot phantom. The 3D models were converted into STL format and sent to the printer. White Ninjaflex™ filament formed the lower substrate of the antenna, and transparent PLA was used for the phantom. The patterns of the antenna were etched on a copper clad Mylar substrate of thickness of 0.05 mm and attached to the flexible PLA substrate using double sided sticky tape. The antenna was fed by an SMA connector as shown in Fig. 1(b). A last foot model with overall dimensions of 280 mm × 102 mm × 111 mm was used for the phantom. The thickness of the outer layer was set to 2 mm. Owing to the large dimensions of the model, it was split into two, printed and then glued together. The phantom was filled with a broadband dielectric tissue equivalent liquid provided by IndexSAR (CTIA Broadband Fluid IXF-CTIA V3.2). Table I shows the characteristic of the tissue equivalent parameters [11].

The antenna was mounted on the bridge of the foot phantom as shown in Fig.4. It was positioned there as the most likely placement when integrated into the tongue of typical footwear.

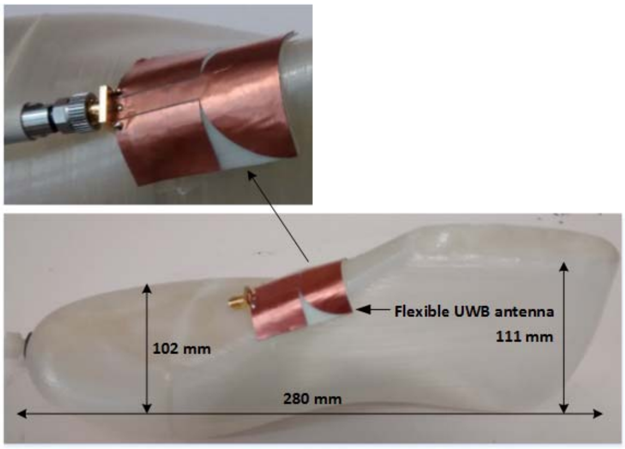
In order to be able to simulate the antenna and phantom, the 3D model (.STL file) for the foot last was imported into the CST Microwave Studio™. A reduced size, 0.8 of the original phantom, was considered as homogenous human body while the rest was used as the outer layer of the transparent PLA material. Owing to the complexity of the model, a homogenous dielectric constant of approximately 30 ($\varepsilon_r = 30$ ) was used for the liquid. This is equivalent two-thirds of the muscle's electrical characteristics [6] which suits well the UWB frequency range.

TABLE I. TISSUE EQUIVALENT PARAMETERS

| *Frequency (MHz)* | *Permittivity* | *Conductivity* |
|---|---|---|
| 2100 | 44.9 | 1.75 |
| 2450 | 43.9 | 2.08 |
| 5200 | 37.6 | 5.32 |
| 5800 | 35.9 | 6.11 |




(a)




(b)

Fig.4. Antenna on the 3D printed foot phantom (a) 3D simulation model (b) photograph of antenna and last foot phantom

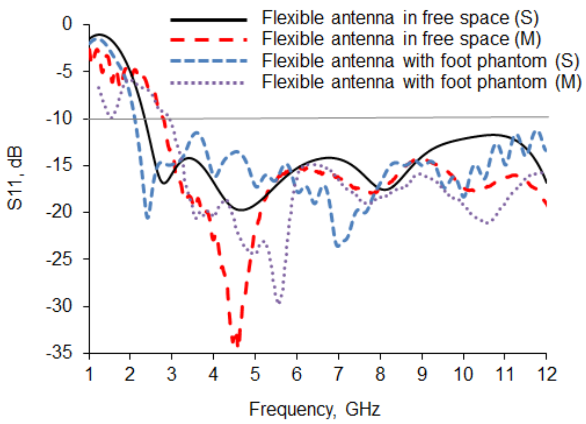



Fig. 5. Reflection coefficient ($S_{11}$) of the flexible UWB antenna with foot phantom without the tissue equivalent liquid (S: Simulation, M: Measurement)

*C. Antenna performance*

The simulated and measured results of the antenna in free space and on the phantom are shown in Fig.5 and Fig.6. The antenna was tested according to the following conditions: 1) in free space 2) with the foot phantom 3) with the foot phantom and the tissue equivalent liquid. Fig.5 compares the results when the foot last is empty, while Fig.6 includes the results for the phantom filled with liquid. After mounting on the foot phantom, there is a shift of the lower frequency to the left side. This is

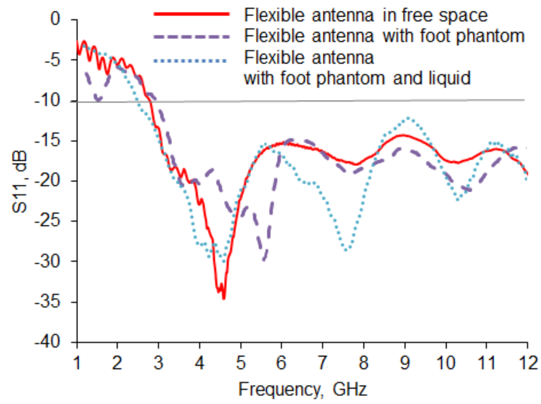



Fig. 6. $S_{11}$ of the flexible UWB antenna with foot phantom and liquid

because of the bending of the antenna and the increase in dielectric permittivity. The antenna operates from 3.1 GHz to over 10.6 GHz for all the configurations tested.

Fig 7, 8 and 9 show the simulated radiation patterns in the XZ, XY and YZ planes for the flexible UWB monopole antenna in free space and on the foot phantom at 3.5 GHz, 6 GHz and 9 GHz. Note that the XYZ planes are in relation to the axis of the antenna as shown in Fig. 4 (a). Omnidirectional radiation pattern is observed in free space. Patterns become more directional when the antenna is placed on the foot phantom. This is due to the lossy dielectric characteristic of the foot phantom which absorbs some of the electromagnetic radiation. Table II compares the computed gain of the antenna in free space with the one on the foot phantom for selected frequencies. The gain of UWB flexible antenna with the foot phantom is greater than the antenna in free space. The radiation efficiency is reduced as shows Table III. As expected, the presence of the foot phantom affects the radiation pattern, gain and efficiency of the antenna.

## III. Conclusion and Discussions

The use of inexpensive additive manufacturing processes for the development of flexible substrates for wearable antenna technology has been demonstrated. 3D printing can also be used for the fabrication of customized foot phantoms. Fuse filament fabrication using PLA materials has been proven to be suitable for these applications. They offer reasonably good electrical properties and fabrication flexibility compared to the commercial laminates. UWB antennas, such as the one employed in this demonstration, allow for the study of changes in input matching and radiation patterns of antennas placed on flexible substrate and phantoms. Simulation and measurement results has shown the expected decrease in resonant frequency when the antenna is close to that of the phantom. Radiation patterns become more directional. The footwear tongue seems to be a good location for flexible wearable antennas intending to communicate with other worn devices or to external electronic systems. An additional advantage is that the tongue can be easily customized by 3D printing and then attach to the footwear.

TABLE II. ANTENNA GAIN

| *Frequency (MHz)* | *Gain (dB) in free space* | *Gain (dB) with a foot phantom and liquid* |
|---|---|---|
| 3500 | 3.37 | 4.59 |
| 5000 | 3.56 | 4.09 |
| 6000 | 2.83 | 5.12 |
| 7000 | 2.69 | 3.93 |
| 9000 | 3.12 | 3.97 |

TABLE III. ANTENNA EFFCIENCY

| *Frequency (MHz)* | *Efficiency (%) in free space* | *Efficiency (%) with a foot phantom and liquid* |
|---|---|---|
| 3500 | 88.5 | 69.7 |
| 5000 | 99.4 | 76.2 |
| 6000 | 95.5 | 66.9 |
| 7000 | 98.4 | 68.7 |
| 9000 | 99.7 | 73.8 |

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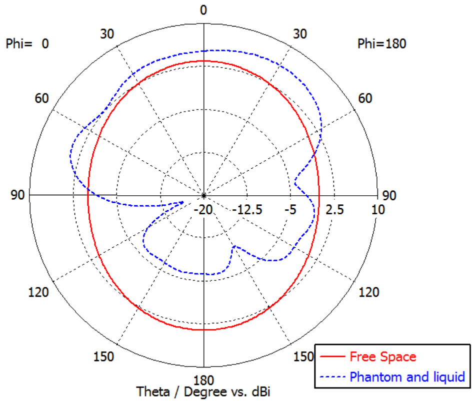
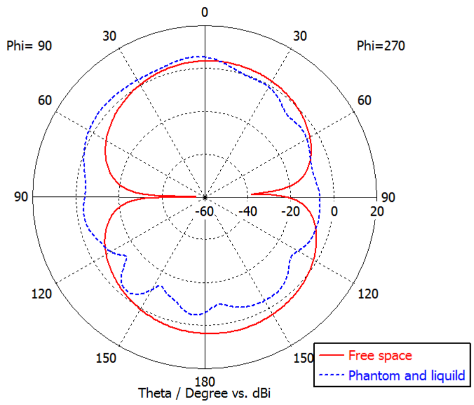
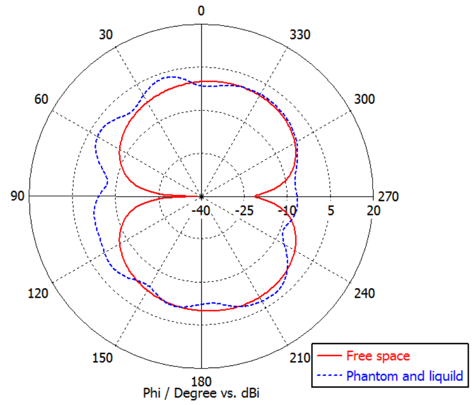



(a) XZ plane

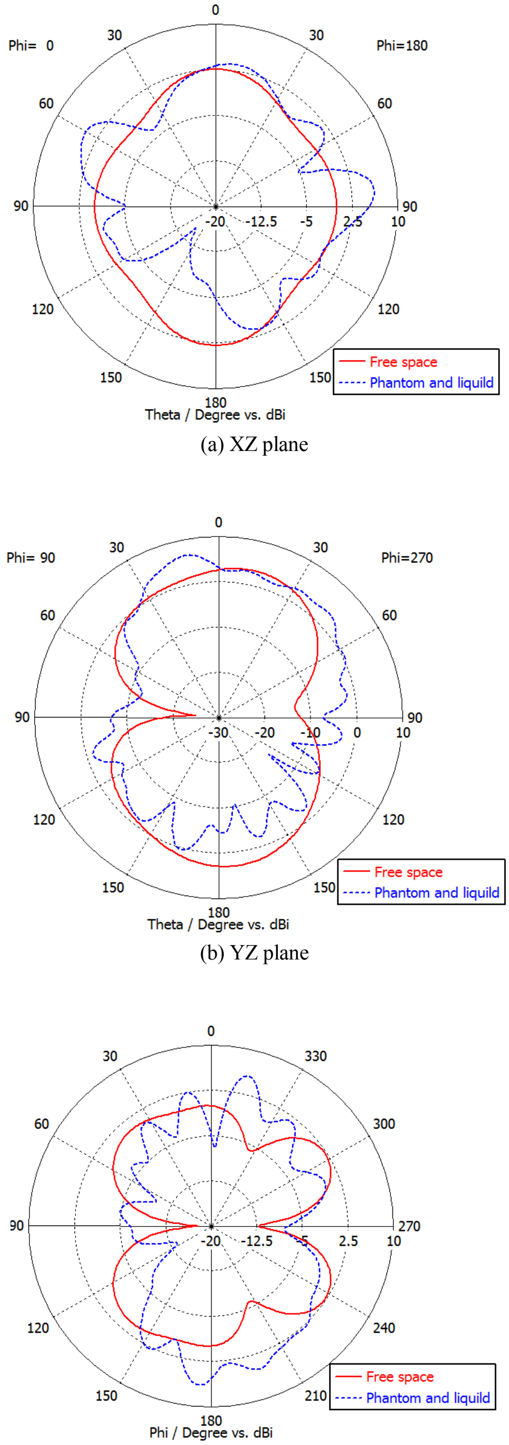



(b) YZ plane




(c) XY plane

Fig. 7. Radiation patterns at 3.5 GHz.

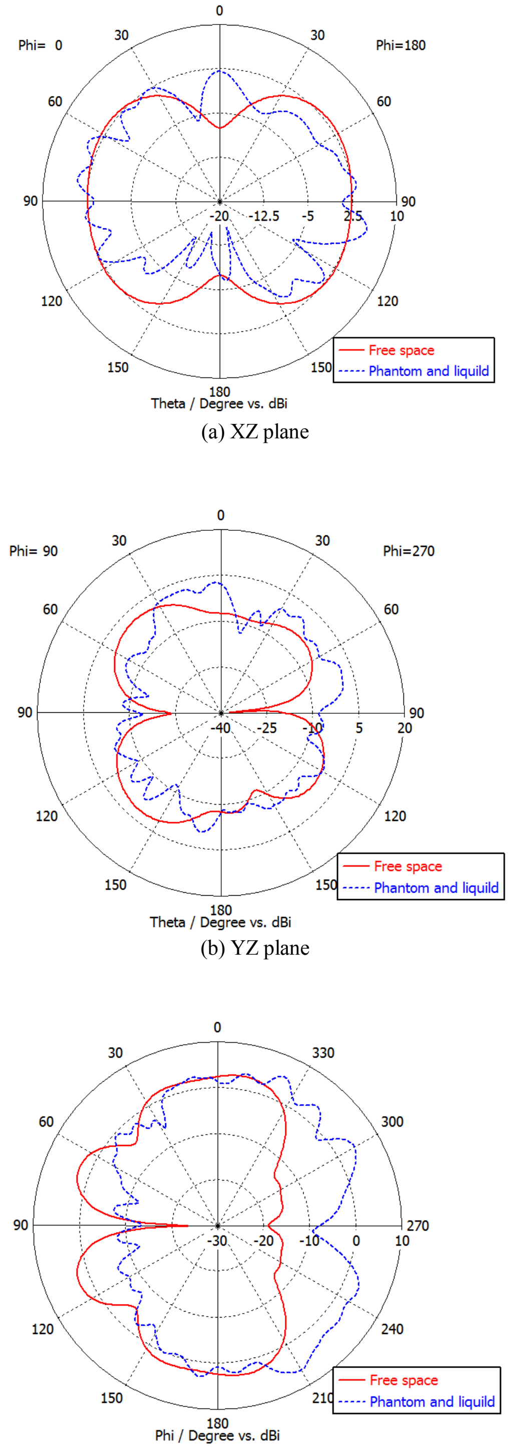



(a) XZ plane

(b) YZ plane

(c) XY plane

Fig. 8. Radiation patterns at 6 GHz.




(a) XZ plane

(b) YZ plane

(c) XY plane

Fig. 9. Radiation patterns at 9 GHz.