We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

4,800

Open access books available

122,000

International authors and editors

135M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Design, Fabrication, and Testing of Flexible Antennas

Haider R. Khaleel, Hussain M. Al-Rizzo and
Ayman I. Abbosh

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/50841

1. Introduction

Recent years have witnessed a great deal of interest from both academia and industry in the field of flexible electronics. In fact, this research topic tops the pyramid of research priorities requested by many national research agencies.

According to market analysis, the revenue of flexible electronics is estimated to be 30 billion USD in 2017 and over 300 billion USD in 2028 [1].

Their light weight, low-cost manufacturing, ease of fabrication, and the availability of inexpensive flexible substrates (i.e.: papers, textiles, and plastics) make flexible electronics an appealing candidate for the next generation of consumer electronics [2]. Moreover, recent developments in miniaturized and flexible energy storage and self-powered wireless components paved the road for the commercialization of such systems [3].

Consistently, flexible electronic systems require the integration of flexible antennas operating in specific frequency bands to provide wireless connectivity which is highly demanded by today's information oriented society.

Needless to say, the efficiency of these systems primarily depends on the characteristics of the integrated antenna. The nature of flexible wireless technologies requires the integration of flexible, light weight, compact, and low profile antennas. At the same time, these antennas should be mechanically robust, efficient with a reasonably wide bandwidth and desirable radiation characteristics.

This chapter deals with the design, numerical simulation, fabrication process and methods, flexibility tests, and measurements of flexible antennas. As a benchmark, a flexible, compact, and low profile (50.8 μm) printed monopole antenna intended for the ISM band applications at 2.45 GHz is presented and discussed in details. The antenna is based on a Kapton Polyi-

mide substrate and fabricated using the ink-jet technology. Finally, the performance of the antenna is compared with different antenna types reported in the literature in terms of electromagnetic performance and physical properties.

Figure 1. Flexible printed monopole antenna based on Kapton Polyimide substrate.

2. Choice of Antenna Substrate

To comply with flexible technologies, integrated components need to be highly flexible and mechanically robust; they also have to exhibit high tolerance levels in terms of bending repeatability and thermal endurance. A plethora of design approaches of flexible and conformal antennas were reported in the literature including Electro-textile [4], paper-based [5], fluidic [6], and synthesized flexible substrates [7]. In [4], a 150 mm × 180 mm flexible Electro textile antenna based on a 4 mm felt fabric is proposed. The antenna operates in the ISM 2.45 GHz band. Although it is suitable for wearable and conformal applications, fabric substrates are prone to discontinuities, fluids absorption, and crumpling.

In [5], a flexible single band antenna printed on a 46mm × 30mm paper-based substrate was proposed for integration into flexible displays for WLAN applications. However, paper based substrates are found to be not robust enough and introduce discontinuities when used in applications that require high levels of bending and rolling. Moreover, they have a relatively high loss factor (loss tangent (tanδ) is around 0.07 at 2.45 GHz) which compromises the antenna's efficiency [8].

Kapton Polyimide film was chosen as the antenna substrate in [9] due to its good balance of physical, chemical, and electrical properties with a low loss factor over a wide frequency

range ($\tan \delta = 0.002$). Furthermore, Kapton Polyimide offers a very low profile (50.8 μm) yet very robust with a tensile strength of 165 MPa at 73°F, a dielectric strength of 3500-7000 volts/mil, and a temperature rating of -65 to 150°C [10]. Other Polymer based and synthesized flexible substrates have been also used in several designs [11-14].

It is worth mentioning that there are several techniques used to characterize the electromagnetic properties of thin and flexible films/substrates such as: the near field microscopy, coplanar waveguide approach, differential open resonator method, and goniometric time-domain spectroscopy method [15-18]. However, the most popular method based on measurements of deposited transmission lines incorporating the material to be characterized which determine the dielectric constants of thin films and the conductivities of the metallic lines over a broad frequency range [19].

3. Choice of Antenna Type

Needless to say, conventional microstrip antennas are not a practical solution for flexible electronics due to their inherently narrow bandwidth which is a function of the substrate's thickness. In [20], a flexible aperture coupled antenna is reported. This technique is known to enhance the impedance bandwidth significantly, however, it leads to an increase in the overall profile; moreover, it involves multi layers, which complicates the fabrication process.

Planar Inverted-F antennas (PIFA) are widely used in mobile phones due the fact that wider impedance bandwidth is obtained despite the presence of a ground plane. Also, antennas incorporating a ground plane promote reduced Specific Absorption Rate (SAR); furthermore, their matching is less affected by the proximity of the human body.

In [21], a 50mm × 19mm textile based broadband PIFA fabricated using conductive textiles is proposed for Wireless Body Area Network (WBAN) applications. Although the antenna exhibits a good impedance bandwidth and radiation characteristics, its overall thickness is 6mm which is considered high for the technology under consideration; moreover, it involves a multi-layer complex, and inaccurate fabrication process.

On the other hand, planar monopole and dipole antennas have received much interest over other antenna types due to their relatively large impedance bandwidth, low profile, ease of fabrication, and omni directional radiation pattern which is highly preferred in many wireless schemes.

Given the technology envisioned in this chapter, Co-Planar Waveguide (CPW) is preferred over other feeding techniques since no via holes or shorting pins are involved, in addition to several useful characteristics such as: low radiation losses, larger bandwidth, improved impedance matching, and more importantly, both radiating element and ground plane are printed on the same side of the substrate, which promotes low fabrication cost and complexity in addition to the capability of roll to roll production.

4. Choice of Fabrication Method

This section reviews the currently available methods for fabrication of flexible and wearable antennas. Method overview, advantages, and drawbacks of each technique are discussed.

4.1. Screen Printing

Screen printing is one of the simplest and most cost effective techniques used by electronics manufacturers. This technique is based on a woven screen that has different thicknesses and thread densities. To produce a printed pattern, a squeegee blade is driven down forcing the screen into contact with the affixed substrate. This in turn forces the ink to be ejected through the exposed areas of the screen on the substrate, and thus, the desired pattern is formed [22]. Polyester and stainless steel are the most common materials used in this technology.

Three different screen printing methods are currently used: flat bed, cylinder, and rotary. Flat bed is the simplest and most common screen printing method. Cylinder screen printing is quite similar to the flat bed except the pattern is deposited as the substrate rotates while attached to the screen roll. In rotary screen, ink and squeegee assembly are rotated inside a rolled screen where impression cylinder produces pressure to substrate [23]. Rotary screen enables much higher throughput capacity than flat bed screen; hence, it is often integrated into a roll to roll production line.
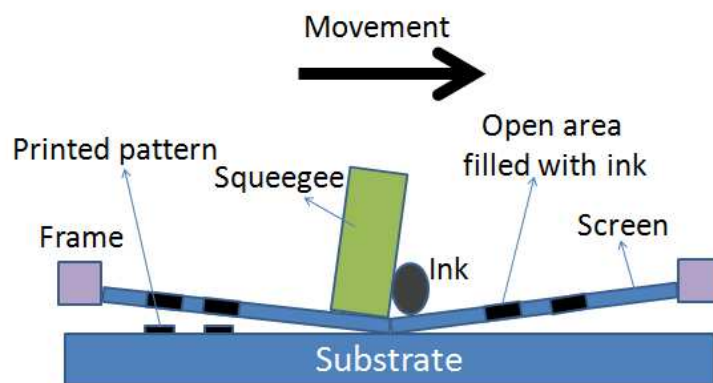
Figure 2. Illustration of the screen printing process.

Screen printing is an additive process as opposed to the subtractive process of chemical etching which makes it a more cost-effective and environmentally friendly. Rather than masking a screen, the patterned mask is applied onto the substrate directly where the conductive ink is administered and thermally cured. Several RFIDs and flexible transparent antennas have been prototyped successfully using this technique [24-26]. However, there are some problems associated with this technique including the limited control over the thickness, number of passes, and resolution of the printed patterns. Layer consistency is also a challenge, as thermal curing of solvent based inks could leave behind artifacts that change

with ink viscosity and surface energy of the substrate [22]. Figure 2 depicts a scheme of the screen printing process.

4.2. Chemical Etching

Chemical etching often accompanied by photolithography is the process of fabricating metallic patterns using a photoresist and etchants to mill out a selected area corrosively. This technique has emerged in the 1960s as a branch-out of the Printed Circuit Board (PCB) industry. Chemical etching gained a wide popularity since it can produce highly complex patterns with high resolution accurately [27].

Photoresist materials are organic polymers whose chemical characteristics change when exposed to ultraviolet light. When the exposed area becomes more soluble in the developer, the photoresist is positive. While if it becomes less soluble, the compound is considered a negative resist.

A major drawback of negative resists is that the exposed regions swell as the counterpart is dissolved by the developer, which compromises the resolution of the process. Swelling occurs due to the penetration of the developer solution into the photoresist material which in turn leads to a distortion in the patterned region [27]. Hence, current practice in the photolithography based antenna and RF circuits Industry relies mainly on positive resists since they present higher resolution than negative resists.
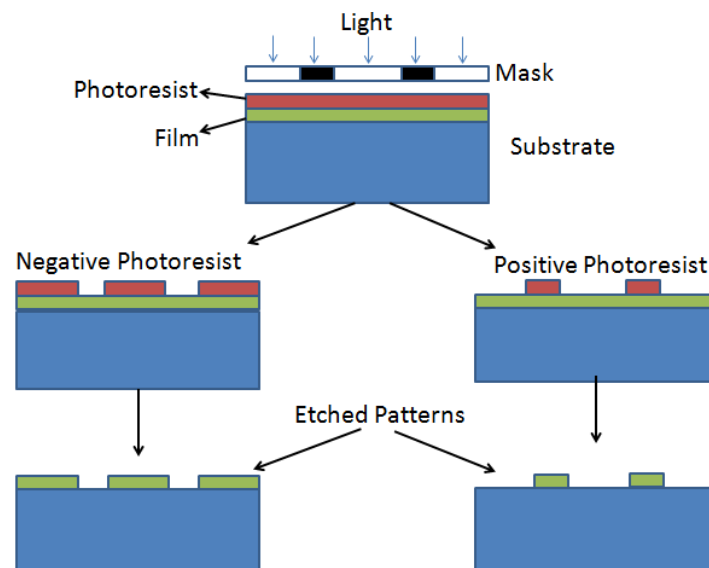

Figure 3. Process flow of the chemical etching (photolithography) process.

Although patterns with high complexity and fine details can be produced using this technique, its lengthy process, low throughput, involvement of dangerous chemicals (neutralization is required), clean room requirement, in addition to byproduct and waste leftovers are major drawbacks of this technology. The reader is referred to [28] for further information on this method. The chemical etching process is illustrated in Figure 3.

4.3. Flexography

Flexography is a type of relief printing. An image is produced by a printmaking process where a protuberating surface of the printing plate matrix is inked while the recessed areas are free of ink. Image printing is a simple process since it only involves inking the protruding surface of the matrix and bringing it in contact with the substrate [29]. Due to its relatively fine resolution, low cost, and high throughput, flexography gained a great interest by RFID antenna manufacturers. Moreover, this technique requires a lower viscosity ink than screen printing inks, and yields imaged (printed) dry films of a thickness of less than 2.5 μm. Hence, flexography inks need to posses higher bulk conductivity than those used in screen printing to compensate for the increase in sheet resistance since the efficiency of printed antennas depends mainly on the electrical conductivity of the traced pattern. Substrate parameters like surface porosity, hydrophobicity, and surface energy have a direct influence on the ink film thickness of the printed trace [23]. The consistency in ink film thickness and line width has also a profound impact on the sheet resistance. The process scheme is demonstrated in Figure 4.
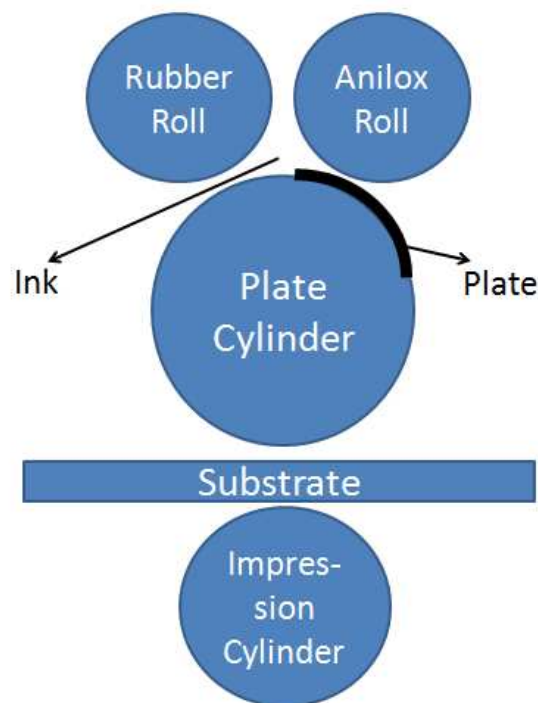
**Figure 4.** Illustration of the flexography printing process based on flexible relief plate.

4.4. Ink Jet Printing

Inkjet printing of RF circuits and antennas using highly conductive inks have become extremely popular in recent years. New inkjet material printers operate by depositing ink droplets of a size down to few pico liters, and hence, these high resolution printers can produce compact designs with tiny details accurately [30].

This new technology utilizes conductive inks based on different nano-structural materials such as silver nano-particle based ink, which is widely used due to its high conductivity. This type of printing technique can be categorized into two types: drop-on-demand and continuous inkjet. Drop on demand print heads apply pressurized pulses to ink with either a piezo or thermo element in which drives a drop from a nozzle when needed. Most printed electronics manufacturers utilize the piezo pulse type [31]. Printing quality depends mainly on the ink characteristics such as viscosity, surface tension, and particle size. The surface topology of the substrate, the platen temperature and the print head parameters are also important factors.

Printing processes and setups are completely controlled from the user's computer, and do not require a clean-room environment which reduces the levels of environmental contamination [31].

Unlike photolithography, which is a subtractive method since it involves removing unwanted pattern from the substrate's metallic/conductive side; inkjet printing deposits a controlled amount of ink droplets from the nozzle to the specified position. Hence, no waste or by-product is produced resulting in an economical, clean, and fast solution. Figure 5 depicts the ink jet printing process.
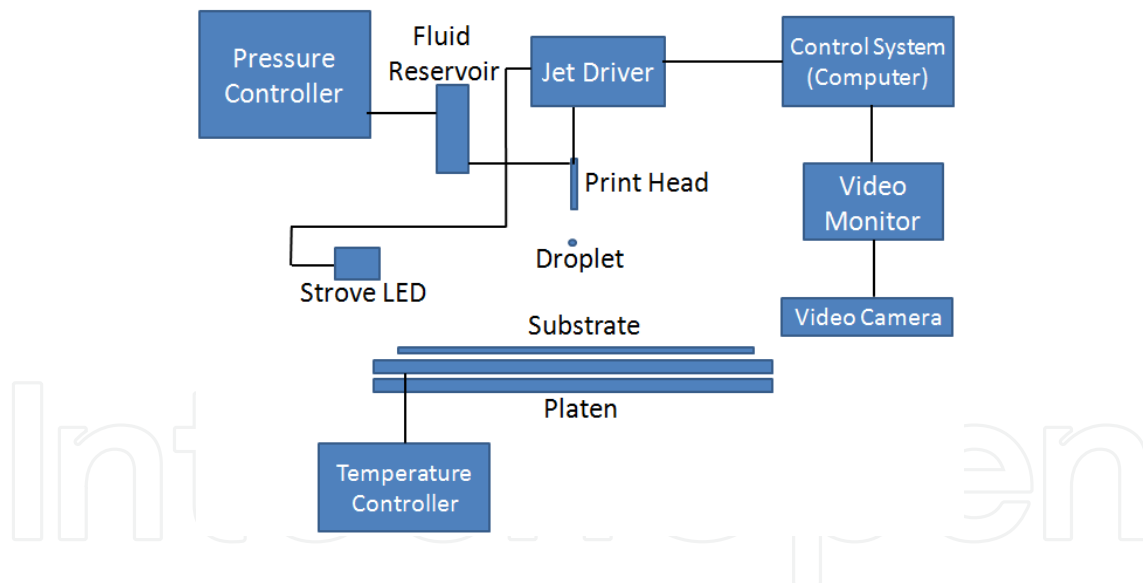
Figure 5. Illustration of the ink jet (droplet on-demand) printing process.

5. Benchmarking Prototype

To benchmark the performance of flexible antennas, a single band printed monopole is presented in this section which has the merits of light weight, ultra low profile (50.8 μm), large bandwidth, robustness, compactness, and high efficiency. The antenna design which is fab-

ricated using the inkjet printing technology covers the ISM 2.45 GHz and fed by a CPW feed. Moreover, the performance of the antenna is evaluated under bending effects in terms of impedance matching and shift in resonant frequency. Finally, the characteristics of the antenna under study are compared to several flexible antenna types reported in the literature.

5.1. ISM Band Printed Monopole Antenna

The ISM 2.45 GHz band is internationally recognized as one the most commonly used standards in wireless communication systems [32]. For example, all of Wireless local-area networks (WLAN), IEEE 802.11/WiFi, Bluetooth and Personal Area Network (PAN) IEEE 802.15.4, ZigBee utilize the ISM 2.45 GHz band. Additionally, several potential applications based on these technologies are possibly applied in the future.

Obviously, the integration of a wireless connectivity based on the abovementioned technologies within flexible devices triggers the need for ultra light/thin/flexible antennas. At the same time, these antennas should be robust, cost effective, and highly efficient with desirable radiation characteristics.

In response to such needs, several design approaches of flexible and conformal antennas based on flexible substrates were reported in the literature [33-39]. In [32], a flexible antenna printed on a 46mm x 30mm paper-based substrate was proposed for integration into flexible displays for WLAN applications. However, paper based substrates are found to be not robust enough and introduce discontinuities when used in applications that require high levels of bending and rolling as mentioned earlier. Moreover, they have a high loss factor (loss tangent (tanδ) is around 0.07 at 2.45 GHz) which compromises the antenna's efficiency. In [34], a stretchable antenna based on an elastic substrate is presented. The design offers a good solution in terms of flexibility and stretchability; however, it involves a complex manufacturing process where the conductors are realized by injecting a room temperature liquid metal alloy into molded micro-structured channels on an elastic dielectric material followed by channels encapsulation. In [35], a conformal exponentially tapered slot antenna based on a 200 μm Liquid Crystal Polymer (LCP) substrate is reported. The design exhibits excellent radiation characteristics; however, the dimensions (130mm × 43mm) are too large for integration within modern compact and flexible electronics. In this section, a flexible compact split ring printed monopole antenna intended for flexible/wearable/conformal applications is presented. The antenna is printed on a 50.8 μm Kapton substrate and fed by a CPW. Both radiating element and ground plane are printed on the same side of the substrate which promotes low fabrication cost and complexity in addition to roll to roll production.

5.1.1. Antenna Design

As shown in Figure 2, the antenna consists of a square split ring shaped radiating element fed by a CPW. The winding lengthens the current path which in turn reduces the structure size without significant efficiency degradation or disturbance to the radiation pattern. The separation distance between the arms is optimized as 5 mm to achieve the least return loss. It is worth mentioning that a smaller separation leads to an increased capacitive coupling

between the arms which in turn degrades the impedance matching. The split ring monopole is fed by CPW feed, which adds the merit of fabrication simplicity since both the radiating element and ground plane are printed on the same side of the substrate.
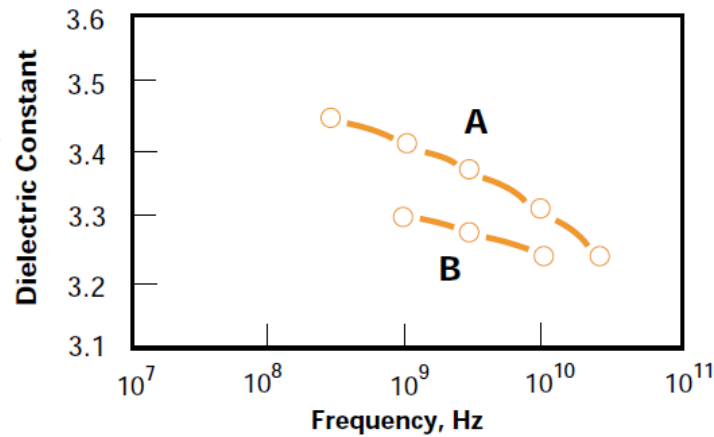
Figure 6. Dielectric constant Vs. frequency for the HN type Kapton polyimide (125 μm). The characteristics are similar to the 50 μm used in the reported prototype. Curve A is for measurement at 25°C (77°F) and 45% RH with the electric field in the plane of the sheet, while Curve B is the same measurement after conditioning the film at 100°C [10].
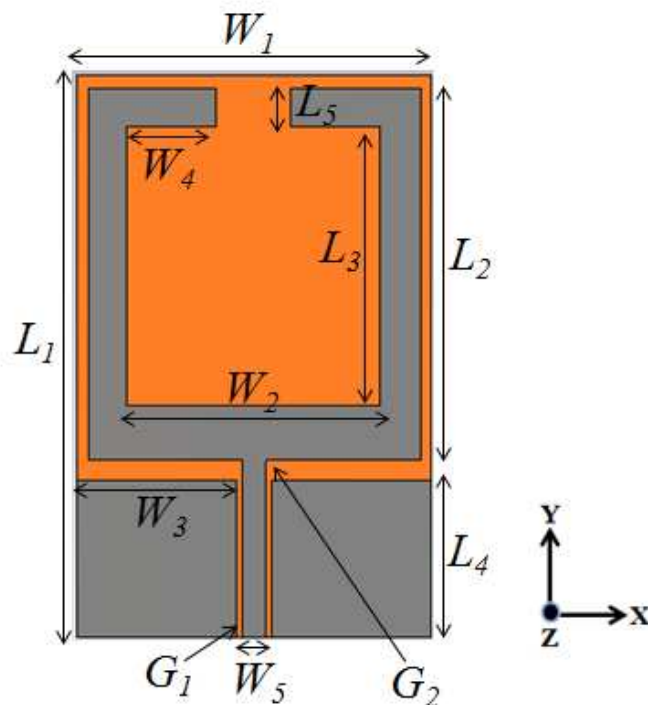
Figure 7. Geometry and dimensions of the reported Split Ring printed monopole antenna (the grey colored area represents the ground plane and the radiating element).

The antenna structure is printed on a 38 mm × 25 mm Kapton Polyimide substrate with a dielectric constant of 3.4 and a loss tangent of 0.002 (dielectric constant versus frequency is provided in Figure 6). The geometry and dimensions of the antenna are depicted in Figure 7 and Table 1.

L_1	38	W_1	25
L_2	26	W_2	18
L_3	19	W_3	10.5
L_4	9.5	W_4	6.5
L_5	3	W_5	2
$G1$	2	$G2$	0.5

Table 1. ISM Band Printed Monopole Antenna Dimensions in Millimeter.

5.1.2. Simulations, Fabrication and Measurements

Design and analysis of the reported printed monopole antennas have been carried out using the full wave simulation software CST Microwave Studio which is based on the Finite Integration Technique (FIT) [40].

To ensure a high simulation accuracy, the number of mesh cells was mainly determined through sufficient meshing of the antenna element where the smallest geometric detail (i.e. CPW gap, microstrip line, etc,..) is covered by at least three mesh cells both horizontally and vertically. The total number of the mesh cells generated for the antenna under study is 498,750 cells.


Figure 8. Installing the polyimide substrate on the platen of the material printer.

Before starting the printing process which is performed using the Dimatix DMP 2831 Fujifilm material printer [41], the final simulated design is exported to the printer using Dima-

tix Drop Manager Software in a Gerber file format which contains all the geometrical dimensions of the antenna design. Moreover, all printing processes and setup conditions can be controlled using the Dimatix Drop Manager software such as the number of layers to be printed, heating temperature of the platen desk, number of nozzles used in operation and height of the cartridge head with respect to the substrate.

A conductive ink based on sliver nano particles is deposited over the substrate utilizing 16 nozzles with 25 μm drop spacing. After the printing process is completed, thermal annealing is required to evaporate excess solvent and to remove ink impurities. Furthermore, the thermal annealing process provides an increased bond of the deposited material. The reported antenna is cured at 100° for 4 hours by a LPKF Protoflow industrial oven. It is worth mentioning that 2 layers of ink were deposited on the substrate to achieve a robust and continuous radiating element and more importantly to increase the electrical conductivity. It should be noted that due to the excellent thermal rating of kapton polyimide (-65 to 150°C), no shrinking was experienced during the annealing process. For measurement purposes, the antenna is fed by a 50 Ω SubMiniature Version A (SMA) coaxial RF connector.
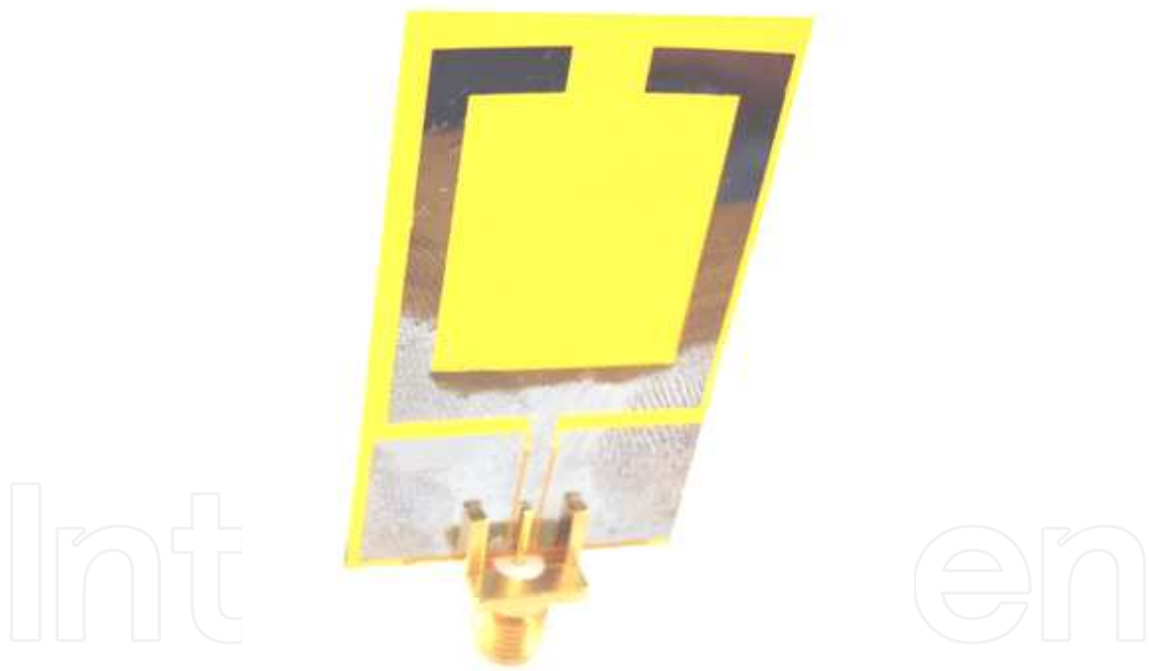
**Figure 9.** Final printed Polyimide based antenna prototype after thermal annealing.

5.2.1. Reflection Coefficient S_{11}

The S-parameters were measured using an Agilent PNA-X series N5242A Vector Network Analyzer (VNA) with (10 MHz-26.5 GHz) frequency range. As can be seen in Figure 10, a good agreement is achieved between the simulated and measured reflection coefficient S_{11} for the

split ring antenna. The simulated return loss for the antenna is 27 dB at 2.45 GHz, with a -10 dB bandwidth of 430 MHz. The measured return loss is -28.5 dB at 2.39 GHz with a -10 dB bandwidth of 540 MHz. The increase in the measured bandwidth is attributed to the decreased electrical conductivity caused by the solvent and impurities found in the silver nano-particle ink, which in turn increases the quality factor and leads to bandwidth enlargement.
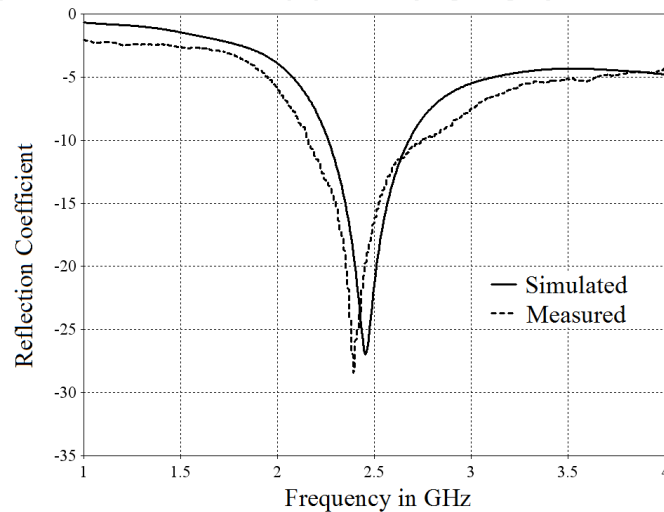
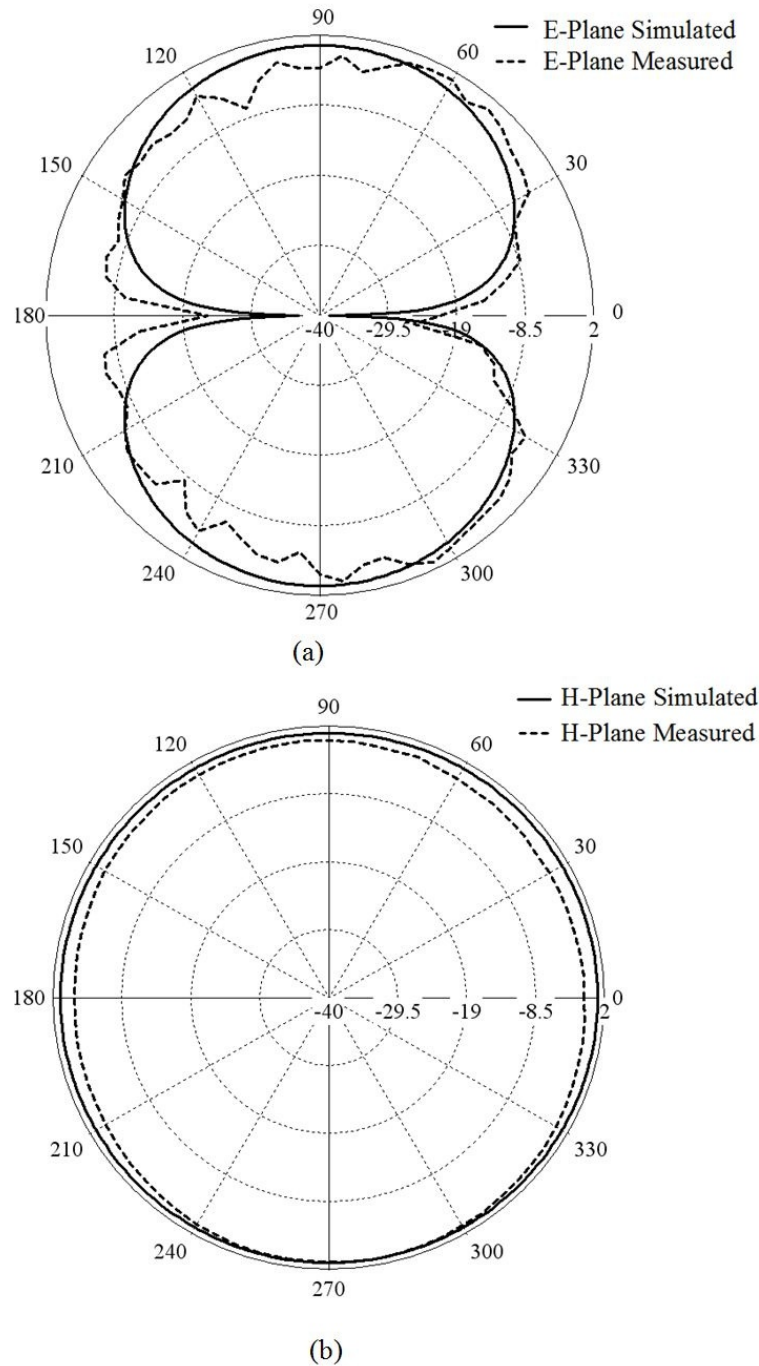**Figure 10.** Measured and simulated reflection coefficient S_{11} for the split ring antenna.

5.2.2 Far-field Radiation Patterns

The far-field radiation patterns of the principal planes (E and H) were measured in a fully equipped anechoic chamber. The Antenna Under Test (AUT) was placed on an ETS Lindgren 2090 positioner and aligned to a horn antenna with adjustable polarization.
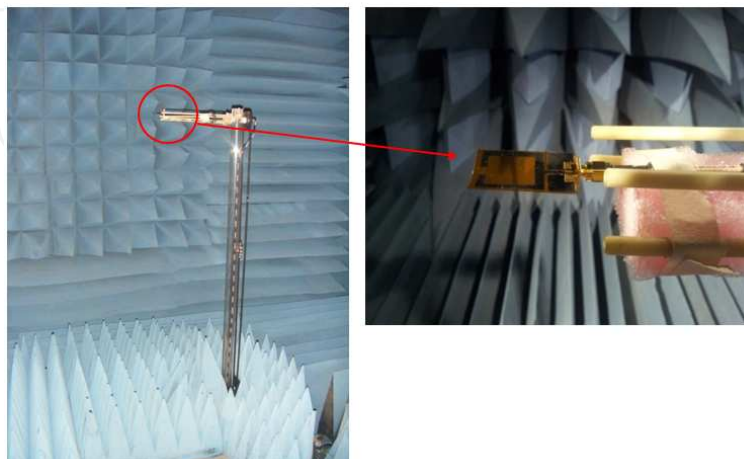
Figure 11. Radiation pattern measurement setup inside an anechoic chamber.

E-plane (YZ cut) and H-plane (XZ cut) far-field radiation patterns are shown in Figure 12. It can be seen that the radiation power is omni-directional at the resonant frequency. The antenna achieved a measured gain of 1.65 dBi which fairly agrees with the simulated value.

Figure 12. Measured and simulated radiation patterns for the split ring printed monopole at 2.45 GHz (a) E-plane (*YZ*) and (b) H-plane (*XZ*).
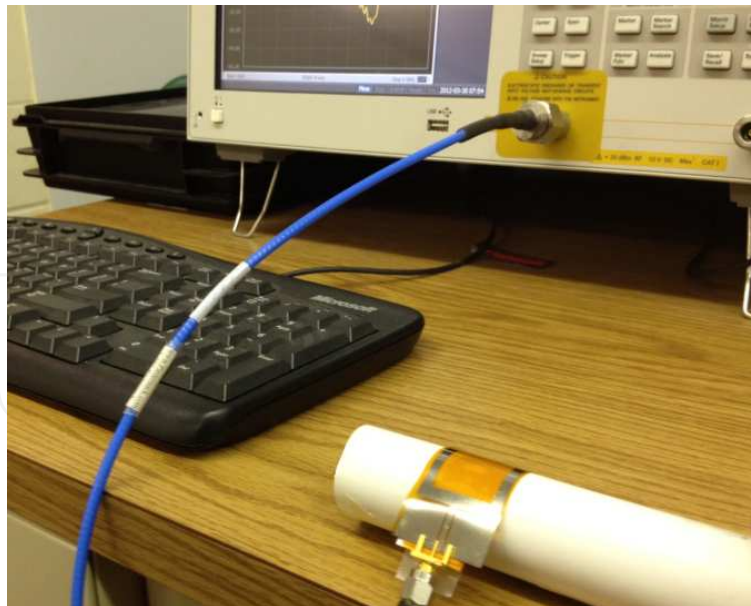
5.2.3. Flexibility Tests

Since the antenna is expected to be bent and rolled when worn or integrated within flexible devices, three tests need to be conducted for operative validation:

- Durability and robustness tests are required, which is performed by repeated testing of the fabricated antennas under bending, rolling and twisting to monitor the deposited conductive ink for any deformations, discontinuities, and to ensure there are no cracks wrinkles or permanent folds are introduced, which might compromise the antennas performance.

- Resonant frequency and return loss need to be evaluated under bending conditions since they are prone to shift/decrease due to impedance mismatch and a change in the effective electrical length of the radiating elements.

- Radiation patterns and gain of the antenna are required to be tested for distortion and/or degradation when conformed on a curved surface.

As stated before, Polyimide Kapton substrate was chosen for this technology mainly due to its physical robustness and high flexibility. Furthermore, the fabricated prototype demonstrated an excellent performance as it was tested repeatedly against bending, twisting, and rolling effects.

AUT is conformed on foam cylinders with different radii (the first is r=10mm and the second is r=8mm) to emulate different extents of bending while it is connected to the network analyzer.


Figure 13. Flexibility test setup (AUT is conformed over a cylindrical foam with different radii to reflect different extents of bending).

As can be seen in Figure 14, around 35 MHz shift to a higher resonant frequency is experienced when the antenna is horizontally conformed on a 10 mm radius cylinder which mim-

ics a moderate extent of bending; while a shift of 80 MHz is observed in the extreme case where the antenna is curved on a 8mm radius foam cylinder, while the antenna is less affected when bent in the vertical plane. However, the impedance bandwidth of the AUT is relatively large, which could overcome the shift caused by the bending effect. Figure 13 shows the flexibility test setup for the dual band antenna rolled on a foam cylinder with an 8 mm radius. Figure 14 depicts the reflection coefficient of the bent cases in both horizontal and vertical planes compared to the flat case.
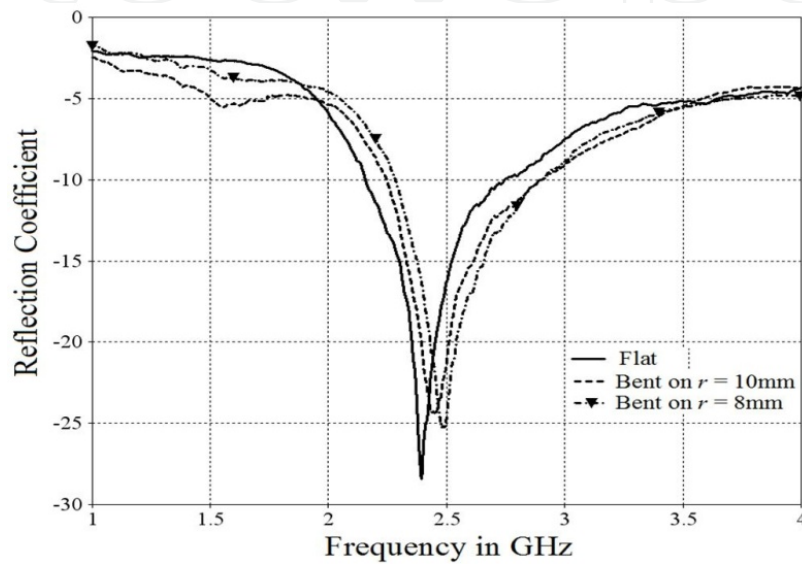
(a)
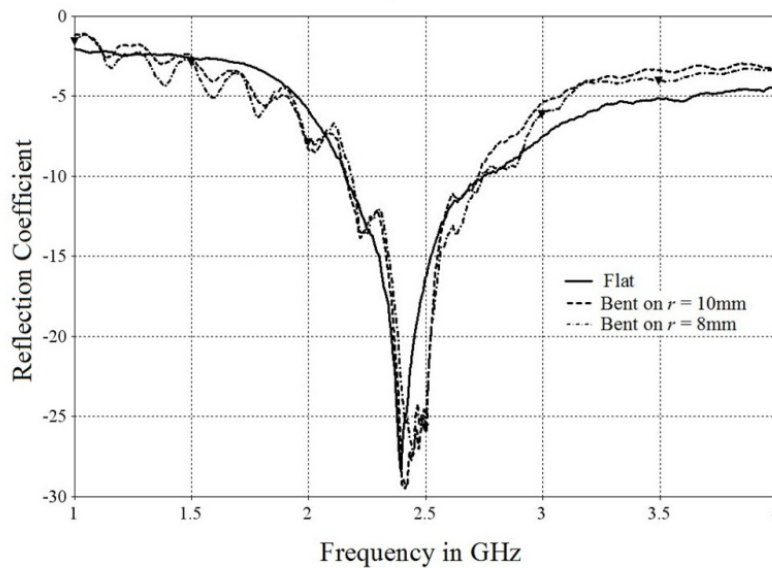
(b)

Figure 14. Measured S_{11} for the reported antenna when bent on a foam cylinder with different radii (r=10 mm and r=8 mm) to mimic different bending extents. (a) horizontal plane, (b) vertical plane.

5.2.4 Comparative Study

The split ring antenna design is compared to different types of flexible antennas reported in [4]-[7]. Given the applications envisioned in this study, the comparative study is focused on compactness (size and thickness), electrical properties and robustness. Robustness encompasses the major mechanical properties related to flexible/conformal electronic devices such as tensile strength, flexural strength, deformability, and thermal stability. Fabrication complexity criterion is also considered in this comparative study. Table 2 depicts these characteristics of the antenna under study.

Character-istics	Polyimide based antenna	Textile antenna [4]	Paper based antenna [5]	Fluidic antenna [6]	Flexible Bow-tie antenna [7]
Size in mm	38 x 27	180 x 150	46 x 35	65 x 10	39 x 25
Thickness mm	0.05	4	0.25	1	0.13
Band/f₀	Single/ 2.45 GHz	Dual/2.2, 3 GHz	Single/2.4 GHz	Variable	Single/7.6 GHz
Substrate	Polyimide ε=3.4	Felt fabric ε=1.5	Paper ε= 3.4	PDMS ε= 2.67	PEN film ε=3.2
Dielectric loss	Low loss tan δ=0.002	Low loss tan δ=0.02	Medium loss tan δ=0.065	High loss tan δ=0.37	Low loss tan δ=0.015
Tensile strength	High (165 MPA)	Low (2.7 MPA)	Low (30 MPA)	Low (3.9 MPA)	High (74 MPA)
Flexural strength	High (50000 p.s.i)	Low (8900 p.s.i)	Low (7200 p.s.i)	Low (650 p.s.i)	High (13640 p.s.i)
Deform-ability	Low	High	High	High	Low
Thermal stability	High	Low	Low	Low	High
Fabrication complexity	Simple/ printable	Complex/Non-printable	Simple/Printable	Complex/Non-printable	Simple/Printable

Table 2. Comparative Study of Different Types of Flexible Antennas.

As shown in Table 2, the antenna reported in this chapter offers a relatively smaller size, highly robust and flexible design. Furthermore, the antenna is printable and provides low cost and roll to roll production.

6. Conclusion

In this chapter, the design, fabrication, and measurement of flexible antennas are discussed in details. Types of substrates and available fabrication methodologies for flexible antennas are reviewed. As a benchmark, a single band printed monopole antenna operating in the

2.45 GHz ISM band is presented which has the merits of light weight, ultra low profile, wide bandwidth, robustness, compactness, and high efficiency. The reported design is based on a Kapton Polyimide substrate which is known for its flexibility, robustness and low dielectric losses. The prototype was fabricated using the inkjet printing technology. Furthermore, the antenna is tested under bending effects since it is expected to be flexed or conformed on curved surfaces. Flexibility, robustness, compactness, fabrication simplicity along with good radiation characteristics suggest that the reported methodology, antenna type and substrate is a reasonable candidate for integration within flexible electronics.

Author details

Haider R. Khaleel[*], Hussain M. Al-Rizzo and Ayman I. Abbosh

*Address all correspondence to: hrkhaleel@ualr.edu

Department of Systems Engineering, University of Arkansas at Little Rock,, USA

References

[1] Hu, J. (2010). Overview of flexible electronics from ITRI's viewpoint. VLSI Test Symposium (VTS), 2010 28th, 19-22 April , 84.

[2] Nathan, A., & Chalamala, B. R. (2005, July). Special Issue on Flexible Electronics Technology, Part 1: Systems and Applications. *Proceedings of the IEEE*, 93(7), 1235-1238.

[3] Yongan, Huang, Chen, Jiankui, Yin, Zhouping, & Xiong, Youlun. (2011). Roll-to-Roll Processing of Flexible Heterogeneous Electronics With Low Interfacial Residual Stress. Components, Packaging and Manufacturing Technology IEEE Transactions on Sept., 1(9), 1368-1377.

[4] Salonen, P., Kim , Jaehoon, & Rahmat-Samii, Y. (2004). Dual-band E-shaped patch wearable textile antenna. *IEEE Antennas and Propagation Society Symposium*, 1, 466-469.

[5] Anagnostou, D. E., Gheethan, A. A., Amert, A. K., & Whites, K. W. (2010, Nov). A Direct-Write Printed Antenna on Paper-Based Organic Substrate for Flexible Displays and WLAN Applications. *Display Technology, Journal of*, 6(11), 558-564.

[6] Masahiro, Kubo., Xiaofeng, Li., Choongik, Kim., Michinao, Hashimoto., Wiley, Benjamin J., Ham, Donhee., & George, M. (2010). White sides Stretchable Microfl uidic Radio frequency Antennas,. *Wiley Inter science, Adv. Mater.*, 22, 2749-2752.

[7] Durgun, A. C., Reese, M. S., Balanis, C. A., Birtcher, C. R., Allee, D. R., & Venugopal, S. (2010, Jul). Flexible bow-tie antennas. *Antennas and Propagation Society International Symposium (APSURSI), 2010 IEEE*, 1.

[8] Yang, L., Rida, A., Vyas, R., & Tentzeris, M. M. (2007). RFID tag and RF structures on a paper substrate using inkjet-printing technology. IEEE Trans. Microw. Theory Techn. pt. 2, Dec., 55(12), 2894-2901.

[9] Khaleel, H. R., Al-Rizzo, H. M., & Rucker, D. G. (2012, Feb). Compact Polyimide-Based Antennas for Flexible Displays. *Display Technology, IEEE Journal of*, 8(2), 91-97.

[10] Du Pont Dupont Kapton Polyimide specification sheet, www2.dupont.com/kapton.

[11] Gheethan, A., & Anagnostou, D. (2012). Dual Band-Reject UWB Antenna with Sharp Rejection of Narrow and Closely-Spaced Bands. Antennas and Propagation, IEEE Transactions on 0.(99), 1.

[12] Scarpello, M. L., Kurup, D., Rogier, H., Vande, Ginste. D., Axisa, F., Vanfleteren, J., Joseph, W., Martens, L., & Vermeeren, G. (2011, Oct). Design of an Implantable Slot Dipole Conformal Flexible Antenna for Biomedical Applications. *Antennas and Propagation, IEEE Transactions on*, 59(10), 3556-3564.

[13] Choi, S. H., Jung, T. J., & Lim, S. (2010, August 19). Flexible antenna based on composite right/left-handed transmission line. *Electronics Letters*, 46(17), 1181-1182.

[14] De Jean, G., Bairavasubramanian, R., Thompson, D., Ponchak, G. E., Tentzeris, M. M., & Papapolymerou, J.. (2005). Liquid Crystal polymer (LCP): a new organic material for the development of multilayer dual-frequency/dual-polarization flexible antenna arrays. *Antennas and Wireless Propagation Letters, IEEE*, 4, 22-26.

[15] Karbassi, A., Ruf, D., Bettermann, A. D., Paulson, C. A., van der Weide, Daniel. W., Tanbakuchi, H., & Stancliff, R. (2008, Sep). Quantitative scanning near-field microwave microscopy for thin film dielectric constant measurement. *Review of Scientific Instruments*, 79(9), 094706-094706-5.

[16] Fratticcioli, E., Dionigi, M., & Sorrentino, R. (2004, Aug). A simple and low-cost measurement system for the complex permittivity characterization of materials. *Instrumentation and Measurement, IEEE Transactions on*, 53(4), 1071-1077.

[17] Dudorov, S. N., Lioubtchenko, D. V., Mallat, J. A., & Raisanen, A. V. (2005, Oct). Differential open resonator method for permittivity measurements of thin dielectric film on substrate. *Instrumentation and Measurement, IEEE Transactions on*, 54(5), 1916-1920.

[18] Ming, Li., Fortin, J., Kim, J. Y., Fox, G., Chu, F., Davenport, T., Toh-Ming, Lu., & Xi-Cheng, Zhang. (2001, Jul/Aug). Dielectric constant measurement of thin films using goniometric terahertz time-domain spectroscopy. *Selected Topics in Quantum Electronics, IEEE Journal of*, 7(4), 624-629.

[19] Janezic, M. D., Williams, D. F., Blaschke, V., Karamcheti, A., & Chi, Shih. Chang. (2003, Jan). Permittivity characterization of low-k thin films from transmission-line measurements. *Microwave Theory and Techniques, IEEE Transactions on*, 51(1), 132-136.

[20] Hertleer, C., Tronquo, A., Rogier, H., Vallozzi, L., & Van Langenhove, L. (2007). Aperture-Coupled Patch Antenna for Integration Into Wearable Textile Systems. *Antennas and Wireless Propagation Letters, IEEE*, 6, 392-395.

[21] Soh, P. J., Vandenbosch, G. A. E., Soo, Liam Ooi, & Rais, N. H. M. (2012, Jan). Design of a Broadband All-Textile Slotted PIFA. *Antennas and Propagation, IEEE Transactions on*, 60(1), 379-384.

[22] Gamota, D. R., Brazis, P., Kalyanasundaram, K., & Zhang, J. (2004). Printed organic and molecular electronics. USA 2004, Kluwer Academic Publishers. 10.1007/978-1-4419-9074-7 , 695.

[23] Halonen, E., Kaija, K., Mantysalo, M., Kemppainen, A., Osterbacka, R., & Bjorklund, N. (2009, 15-18 June). Evaluation of printed electronics manufacturing line with sensor platform application. Paper presented at Microelectronics and Packaging Conference, 2009. EMPC 2009. European,. 1-8.

[24] Kirsch, N. J., Vacirca, N. A., Plowman, E. E., Kurzweg, T. P., Fontecchio, A. K., & Dandekar, K. R. (2009, 27-28 April). Optically transparent conductive polymer RFID meandering dipole antenna. Paper presented at RFID, 2009 IEEE International Conference on. 278-282.

[25] Kirsch, N. J., Vacirca, N. A., Kurzweg, T. P., Fontecchio, A. K., & Dandekar, K. R. (2010, 11-13 Oct.) Performance of transparent conductive polymer antennas in a MIMO ad-hoc network. Paper presented at Wireless and Mobile Computing, Networking and Communications (WiMob), 2010 IEEE 6th International Conference on. 9-14.

[26] Leung, S. Y. Y., & Lam, D. C. C. (2007, July). Performance of Printed Polymer-Based RFID Antenna on Curvilinear Surface. *Electronics Packaging Manufacturing, IEEE Transactions on*, 30(3), 200-205.

[27] Kirschman, R. (1999). *Fabrication of Passive Components for High Temperature Instrumentation*, Wiley-IEEE, 679-682.

[28] Mitzner, Kraig. (2009). Complete pcb design using orcad capture and pcb editor. Publisher: Newnes; Pap/Cdr edition

[29] Niir Board. (2011). *Handbook On Printing Technology (offset, Gravure, Flexo, Screen) 2nd*.

[30] Lakafosis, V., Rida, A., Vyas, R., Li, Yang., Nikolaou, S., & Tentzeris, M. M. (2010, Sept). Progress Towards the First Wireless Sensor Networks Consisting of Inkjet-Printed, Paper-Based RFID-Enabled Sensor Tags. *Proceedings of the IEEE*, 98(9), 1601-1609.

[31] Orecchini, G., Alimenti, F., Palazzari, V., Rida, A., Tentzeris, M. M., & Roselli, L. (2011, June 6). Design and fabrication of ultra-low cost radio frequency identification

antennas and tags exploiting paper substrates and inkjet printing technology. *Microwaves, Antennas & Propagation, IET*, 5(8), 993-1001.

[32] Mitilineos, S. A., & Capsalis, C. N. (2007, Sept). A New, Low-Cost, Switched Beam and Fully Adaptive Antenna Array for 2.4 GHz ISM Applications. *Antennas and Propagation, IEEE Transactions on*, 55(9), 2502-2508.

[33] Anagnostou, D. E., Gheethan, A. A., Amert, A. K., & Whites, K. W. (2010, Nov). A Direct-Write Printed Antenna on Paper-Based Organic Substrate for Flexible Displays and WLAN Applications. *Display Technology, Journal of*, 6(11), 558-564.

[34] Shi, Cheng., Zhigang, Wu., Hallbjorner, P., Hjort, K., & Rydberg, A. (2009, Dec). Foldable and Stretchable Liquid Metal Planar Inverted Cone Antenna. *Antennas and Propagation, IEEE Transactions on*, 57(12), 3765-3771.

[35] Symeon, Nikolaou., Ponchak, G. E., Papapolymerou, J., & Tentzeris, M. M. (2006, June). Conformal double exponentially tapered slot antenna (DETSA) on LCP for UWB applications. *Antennas and Propagation, IEEE Transactions on*, 54(6), 1663-1669.

[36] Srifi, M. N., Podilchak, S. K., Essaaidi, M., & Antar, Y. M. M. (2011, Dec). Compact Disc Monopole Antennas for Current and Future Ultrawideband (UWB) Applications. *Antennas and Propagation. IEEE Transactions on*, 59(12), 4470-4480.

[37] Bae, Su Won, Yoon, Hyung Kuk, Kang, Woo Suk, Yoon, Young Joong, & Lee, Cheon-Hee. (2007). A Flexible Monopole Antenna with Band-notch Function for UWB Systems. Microwave Conference, 2007. APMC 2007. Asia-Pacific 11-14 Dec., 1-4.

[38] Jung, J., Lee, H., & Lim, Y. (2009, Mar). Broadband flexible comb-shaped monopole antenna. *Microwaves, Antennas & Propagation, IET*, 3(2), 325-332.

[39] Shaker, G., Safavi-Naeini, S., Sangary, N., & Tentzeris, M. M. (2011). Inkjet Printing of UWB Antennas on Paper-Based Substrates. *Antennas and Wireless Propagation Letters, IEEE*, 10, 111-114.

[40] CST. http/www.cst.com.

[41] Fuji Film. http://www.fujifilmusa.com/products/industrial_inkjet_printheads/deposition-Products/dmp-2800/index.html.

[42] Haga, N, Takahashi, M., Ito, K., & Saito, K. (2009). Characteristics of cavity slot antenna for Body-Area Networks. *IEEE Trans. on Antennas and Propag.*, 57(4), 837-843.

[43] Lin, C. C., Kuo, L. C., & Chuang, H. R. (2006, Nov). A Horizontally Polarized Omnidirectional Printed Antenna for WLAN Applications. *Antennas and Propagation, IEEE Transactions on*, 54(11), 3551-3556.

[44] Qi, Luo., Pereira, J. R., & Salgado, H. M. (2011). Compact Printed Monopole Antenna With Chip Inductor for WLAN. *Antennas and Wireless Propagation Letters, IEEE*, 10, 880-883.

[45] Wu, J. W., Hsiao, H. M., Lu, J. H., & Chang, S. H. (2004, Nov). Dual broadband de-
sign of rectangular slot antenna for 2.4 and 5 GHz wireless. *IEEE Electron. Lett.*,
40(23).

[46] Raj, R. K., Joseph, M., Aanandan, C. K., Vasudevan, K., & Mohanan, P. (2006, Dec). A
new compact microstrip-fed dual-band coplanar antenna for WLAN applications.
IEEE Trans. Antennas Propag., 54(12), 3755-3762.

[47] Chen, H. D., Chen, J. S., & Cheng, Y. T. (2003, Oct). Modified inverted-L monopole
antenna for 2.4/5 GHz dual-band operations. *IEEE Electron. Lett.*, 39(22).