Inkjet-printed patch antenna emitter for wireless communication application

Goh, Guo Liang; Ma, Jiaheng; Chua, Francis Kwee Lim; Shweta, Agarwala; Yeong, Wai Yee; Zhang, Yue Ping

2016

Goh, G. L., Ma, J., Chua, F. K. L., Shweta, A., Yeong, W. Y., & Zhang, Y. P. (2016). Inkjet-printed patch antenna emitter for wireless communication application. *Virtual and Physical Prototyping*, 11(4), 289-294. doi:10.1080/17452759.2016.1229802

<https://hdl.handle.net/10356/146084>

<https://doi.org/10.1080/17452759.2016.1229802>

This is an Accepted Manuscript of an article published by Taylor & Francis in *Virtual and Physical Prototyping* on 23 Sep 2016, available online:
<http://www.tandfonline.com/10.1080/17452759.2016.1229802>

Downloaded on 26 Apr 2023 15:25:51 SGT

Inkjet-printed patch antenna emitter for wireless communication application

Goh Guo Liang^{1,3}, Ma Jiaheng², Francis Chua Kwee Lim², Shweta Agarwala¹,
Yeong Wai Yee^{1,3}, Zhang Yue Ping²

¹Singapore Centre for 3D Printing, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

²School of Electrical & Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

³School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

Corresponding Author: Yeong Wai Yee, Email: wyyeong@e.ntu.edu.sg

Inkjet-printed patch antenna emitter for wireless communication application

Abstract: This research focuses on exploring low cost and rapid production solutions for fabricating emitters for patch antennas for wireless communication applications. Additive manufacturing technique is employed to fabricate two patch antennas using silver nanoparticle ink on FR4 substrate. Finite element simulation software, HFSS is used to analyze and predict the theoretical performance of the antenna designs for 2.4 GHz MIMO and 6 GHz wireless data transmission. The fabricated antennas have resonant frequencies closely matching the design values. The work provides a viable solution for fabricating emitters and finally antennas commercially using inkjet printing platform, thus overall reducing the cost and simplifying the process.

Keywords: Printed antenna, Silver ink, Inkjet printing, Additive manufacturing, Antenna design

1. Introduction

Micro strip patch antenna is a low profile antenna consisting of planar conductive patches of varied shapes on one side of dielectric substrates and a ground plane on another side. It is typically used in wireless applications that require hemispherical coverage. Compared to other antennas (such as micro strip dipole and micro strip slot antennas), micro strip patch antenna gives engineers more freedom to design the antenna's bandwidth. The reported bandwidth for patch antennas is as low as 2% to as high as 50% (Singh & Tripathi 2011).

Fabrication of patch antennas, conventionally, is achieved through techniques like i) printed circuit board wet etching (Tong *et al.* 2001, Li *et al.* 2001, Jackson Jr & Ramadoss 2006); ii) copper etched flexible film glued on plastic (Maddela *et al.* 2007, Heikkinen *et al.* 2007) and iii) 3D masking, laser etching or molding of plastic (Su *et al.* 2014, Sekiya *et al.*

2006, Tiercelin *et al.* 2006). Recent advances in electronics and other similar areas require antennas to be multi-functional and cost-effective (Tong *et al.* 2015, Leng *et al.* 2016, Workman *et al.* 2015, Anagnostou & Iskander 2015, Froehle *et al.* 2015, Inui *et al.* 2015). Conventional fabrication techniques have several constraints and hence, cannot be directly applied to fabricate new-age antennas. This has fueled the demand to look for alternative fabrication processes. Low-temperature processing, low cost, robustness and flexibility are some requirements that need to be met by the alternative processes. Recently screen and gravure printing have been widely explored to fabricate electronics due to their excellent speed and resolution (Agarwala *et al.* 2010, Agarwala *et al.* 2012, Agarwala *et al.* 2013, Li *et al.* 2015, Valmiro *et al.* 2015, Lu *et al.* 2014, Zhu *et al.* 2014). However, these are contact printing techniques, which can lead to contamination of printed parts (Li *et al.* 2015). Also, fabrication processes requires some pre-fabrication work such as preparation of masks, thus making the whole process tedious and lengthy (Lu *et al.* 2014).

Additive manufacturing, also known as 3D printing, is a group of techniques where a component is built layer-by-layer through depositing material (Sing *et al.* 2015, Lee *et al.* 2016, Yeong *et al.* 2005, Chua *et al.* 2005). Additive manufacturing possesses the ability to fabricate complex parts directly from design files without the need for tooling. Another advantage is adaptability to wide range of materials like thermoplastic, metal, ceramic, composites and bio-materials (Wang *et al.* 2015, Sing *et al.* 2016, Yeong *et al.* 2013). Additive manufacturing enables to create complex structures with low cost and high speed. Inkjet printing, a kind of additive manufacturing technique, has been investigated mainly for electronic materials (Mäntysalo & Mansikkamäki 2009). It is a non-contact process that selectively deposits a wide range of materials onto a wide range of substrates in a drop-by-drop manner. Compatibility with various substrates, reduced material waste and good

resolution/ feature size gives inkjet printing a competitive edge over traditional manufacturing methods.

Here, inkjet printing is used to fabricate emitters for 2.4 GHz and 6 GHz patch antennas for wireless data communication. The antenna design chosen is appropriate for unidirectional radiation and can be easily integrated with small appliances. Various printing parameters are studied to optimize the design and finally the device performance is measured corresponding to S-parameters, and compared with simulated results. This work demonstrates a possibility of adopting additive manufacturing technology for electronic industry.

2. Antenna design and configuration

Microstrip patch antenna was chosen as their performances can be accurately simulated and also easily fabricated using inkjet printing technique. The designs used in this work favors unidirectional radiation and are discussed below.

2.1 Design 1 – 2.4GHz

The objective and targeted application of 2.4GHz microstrip patch antenna is to function as a multiple-input-multiple-output (MIMO) antenna. It consists of two similar orthogonally-oriented rectangular patches with dimension 28.7 mm x 38 mm. The radiating patches are designed to have radiation normal to the patch and pointing away from the ground plane, when printed on FR4 substrates (100 mm x 50 mm x 1.6 mm). The coaxial feed point is located 7.9 mm away from the longer patch edge and equidistant from the two shorter edges. The detail schematic diagram of the antenna design is shown in fig 1(a).

2.2 Design 2 – 6GHz

The antenna design shown in fig 1(b) is targeted for 6 GHz wireless data transmission. Unlike the previous design, this antenna has only one rectangular patch with dimension of 15.2 mm x 10.7 mm. The dimension of the FR4 substrate used is 50 mm x 50 mm x 1.6 mm. The coaxial feed point is designed 1.7 mm away from longer edge and equidistant from the two shorter edges.

Figure 1: Schematic diagram showing physical dimensions of the printed patch antennas (a) 2.4 GHz and (b) 6 GHz.

3. Materials

3.1 FR4 substrate

The FR4 substrate is a common material used for PCB and antenna fabrication. It is made of glass reinforced epoxy laminate sheet with overall thickness of 1.6 mm, and also includes a layer of 0.03 mm copper cladding layer underneath. The glass transition

temperature of the substrates ranges from 120 °C to 180 °C. The dielectric constant of the substrate is approximately 4.4 with a tangent loss of 0.02.

3.2 Conductive silver nanoparticle ink

Commercial silver ink (UTDAg from UT Dots Inc.) is used for printing the antenna. The ink loading is approximately 60% by weight stabilized silver nanoparticles dissolved in organic solvent. The average size of the silver nanoparticle is ~ 10 nm. Viscosity of the ink was tailored to suit the inkjet printing process.

4. Antenna Fabrication

4.1 Inkjet printing

Fujifilm Dimatix DMP-2800 inkjet printer is employed to print the antenna design on the substrate. A DMC-11600 series cartridge is filled with 1.5 ml of ink. Each nozzle has a diameter of 21.5 μm and is capable of jetting 10 pico-liter droplet. The droplet typically forms a spot size of 40 μm diameter. Prior to printing, the FR4 substrate is cleansed with distilled water to remove contaminants such as oil, which may affect the adhesion of the ink. FR4 substrate is then carefully aligned on the printing platform. The cartridge temperature and platform temperature are set to 40 °C and 50 °C respectively. The printing parameters were optimized to achieve a good resolution. A drop spacing of 50 μm was used to achieve a continuous pattern. Two print passes were employed to eliminate possible cracks and non-uniformity of deposited silver ink.

4.2 Thermal sintering

The printed pattern was sintered in a convection oven at a temperature lower than the glass-transitioning temperature of the FR4 substrate. Antenna pattern is heat treated at 135 °C for

120 min. The substrate is immediately removed after 120 min and cooled to room temperature.

4.3 Drilling and soldering

The integration of the SMA RF connectors to the antennas requires drilling and soldering. Drilling of the holes is done after the inkjet printing process, to ensure precise drilling at the desired position. 1.5 mm diameter hole were drilled for the coaxial feed point. The surrounding copper (within 3.5 diameter of the hole) was scraped away to avoid short circuiting the ground plane. The SMA RF connectors are soldered to the ground plane (copper side). However, it was found that the same soldering technique does not work on the silver patch. Hence, cold soldering technique is used instead to connect the silver patch to the cable. MG Chemical 8330s silver conducting epoxy is then used. Finally the fabricated antennas are sintered at 135 °C for 45 min to cure the conducting epoxy.

5. Characterization and Simulation

The printed silver ink pattern was imaged using scanning electron microscope, SEM (JEOL JSM- 5600LV, 10 kV). The antenna is designed using ANSYS High-frequency structural simulator (HFSS). The simulation is carried out in air, which has relative permittivity, $\epsilon_r = 1.00$ and conductivity, $\sigma = 5.5 \times 10^{-15}$ S/m. The substrate dielectric property is assumed to be the same as stated in section 3.1. The resistance of the printed silver pattern is approximately 10 $\mu\Omega$ -cm at sintering temperature of 130 °C for 120 min. Antenna characterization was carried out in an anechoic chamber and the parameters were analyzed by a vector network analyzer.

6. Results and Discussion

The antenna designs were optimized for good impedance match. The design parameters for the patch antennas are indicated in Table 1.

Table 1: Optimized design parameters of inkjet printed antennas.

Substrate	2.4 GHz	6 GHz
Thickness (mm)	1.6	
Permittivity	4.4	
Dimension (mm)	100 x 50	50 x 50
Antenna		
DC Conductivity (S/m)	60×10^3	
Film Thickness (μm)	1.0	
Length (mm)	38	15.2
Width (mm)	28.7	10.6
Feed Point	7.9	1.7

The silver ink patterns were inkjet printed on FR4 substrate to fabricate the antennas. Two print passes were employed to obtain the desired thickness and uniformity of the silver film. Figure 2 a and b show the 2.4 GHz MIMO and 6 GHZ patch antennas respectively. The image of figure 2c also depicts on how the connections were made for measurements. Inkjet printing technique produced uniform and crack-free silver films for antenna application (figure 2d). The nanoparticles are closely packed and provide efficient path for the electrons to flow.

Figure 2: Images of (a) 2.4 GHz MIMO, (b) 6 GHz antenna and (c) drilling and soldering for connection points. (d) Shows the SEM micrograph of the printed silver on FR4 substrate.

Finally, the printed antenna parameters were measured by a vector network analyzer. The measured and simulated frequency response of the 2.4 GHz MIMO and 6 GHz antennas are shown in fig 3. The S-Parameters measurements are done to determine the return loss and isolation of the fabricated prototype. Considering that there are two antennas for the 2.4 GHz MIMO design, the return loss of each is determined by their individual S11 and S22 parameters. S11 measures the reflected power when transmitting via antenna 1 and S22 measures the reflected power when transmitting via antenna 2. As a lower return loss translates to higher efficiency, the resonant frequency of the prototype is determined at the point of the lowest return loss. Based on the experimental results, both antennas of the prototype operate within the frequency of 2.4 GHz. Likewise; the measured resonant frequency for 6 GHz antenna is computed to be 6.11 GHz.

Figure 3: Plotted frequency response of the antennas (a) S11 parameter, (b) S22 parameter, and (c) S21 parameter for 2.4 GHz MIMO antenna and (d) S11 parameter for 6 GHz antenna.

The operating bandwidth of both antennas can be determined from their respective return loss plots. This figure is indicated by the point where the return losses fall below -10 dB. As can be observed in the graph (figure 3a), the 2.4 GHz MIMO antenna have an operating bandwidth of approximately 50 MHz ranging from 2.36 to 2.41 GHz. Figure 3b depicts the operating bandwidth to be 250 MHz for the 6 GHz antenna design.

It is to be noted that the 2.4 GHz design incorporated two antennas to fulfill the criteria of MIMO. Hence, it is important to introduce some degree of isolation while taking measurements. This basically means measuring the coupling between the two antennas on

the same substrate. Mostly large isolation is desirable for MIMO application to achieve low coupling. Isolation is determined by S_{21} or S_{12} parameter, which measures the power received by one antenna when the other is transmitting. Low value of S_{21} or S_{12} indicates higher isolation. The experimental results indicate that the values of S_{21} falls below -40 dB, which provides sufficient isolation between the two printed antennas. The performance parameters of the inkjet printed antennas are summarized in Table 2.

Table 2: Inkjet printed antenna performance parameters.

Antenna	Bandwidth (MHz)		Resonant frequency (GHz)	
	Simulation	Measurement	Simulation	Measurement
2.4GHz	60	50	2.40	2.38
6GHz	200	250	6.05	6.11

The simulated and measured results obtained show good agreement with each other. Only minor differences were observed between simulated and experimental results from the various S-Parameters plots. The small discrepancies can be attributed to the fabrication and measurement tolerances. It is to be understood that the simulation assumes perfect conditions like materials with perfect properties and no loss electrical connections. Thus, the results obtained through simulation are slightly deviated from real values. The shift in the resonant frequency of the antennas can be attributed to inaccurate feed point location. For instance, a shorter distance between the feed point and the nearest patch edge in fabrication will result in a larger resonant frequency for the 6 GHz antenna. However, the performance of the antennas are well-within the tolerance range and the operating

bandwidth of the experimental results aligns with the simulation. This work thus opens doors for actively utilizing inkjet printing for not only fabricating emitters but entire antennas.

7. Conclusions

In this article, we present an unconventional way of fabricating emitters for patch antennas through inkjet printing technique using silver metal nanoparticle ink. The proposed methodology aims at providing a fast and simple solution to design and print two microstrip patch antennas of 2.4 GHz MIMO and 6 GHz. The proposed antennas are lightweight and compact, and thus can be adapted for various applications such as aerospace communication. The printed antenna performance agrees well with the simulated test results. In brief, this work opens avenues for exploring additive manufacturing, i.e. inkjet printing technique, for fabrication of functional electronics.

Acknowledgments

This work was supported under the grant by National Research Foundation (NRF).

References

- Agarwala S., Kevin M., Wong A., Peh C., Thavasi V., Ho G., 2010, ACS applied materials & interfaces, 2, 1844
- Agarwala S., Lim Z., Nicholson E., Ho G., 2012, Nanoscale, 4, 194
- Agarwala S., Ong W., Ho G., 2013, Science of Advanced Materials, 5, 1418
- Anagnostou D., Iskander M., 2015, Aerospace Conference, 2015 IEEE. IEEE, p. 1
- Chua C.-K., Yeong W.-Y., Leong K.-F., 2005, Proc. 2nd Int. Conf. on Advanced Research in Virtual and Rapid Prototyping. p. 19
- Froehle P., Przybylski T., McDonald C., Mirzaee M., Noghianian S., Fazel-Rezai R., 2015, Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2015 IEEE International Symposium on. IEEE, p. 1214
- Heikkinen J.J., Laine-Ma T.T., Kivikoski M.A., 2007, Antennas and Propagation Society International Symposium, 2007 IEEE. IEEE, p. 4168

Inui T., Koga H., Nogi M., Komoda N., Suganuma K., 2015, *Advanced Materials*, 27, 1112

Jackson Jr R., Ramadoss R., 2006, *Journal of Micromechanics and Microengineering*, 17, 1

Lee J.M., Zhang M., Yeong W.Y., 2016, *Microfluidics and Nanofluidics*, 20, 1

Leng T., Huang X., Chang K., Chen J., Abdalla M., Hu Z., 2016,

Li K., Cheng C., Matsui T., Izutsu M., 2001, *Antennas and Propagation Society International Symposium*, 2001. IEEE. IEEE, p. 402

Li Y.L., Zhao F.Y., Li L.H., 2015, *Applied Mechanics and Materials*. Trans Tech Publ, p. 81

Lu J.D., Deng P.J., Li L.H., Li W.W., 2014, *Advanced Materials Research*. Trans Tech Publ, p. 1142

Maddela M., Ramadoss R., Lempkowski R., 2007, *Journal of Micromechanics and Microengineering*, 17, 812

Mäntysalo M., Mansikkamäki P., 2009, *AEU-International Journal of Electronics and Communications*, 63, 31

Sekiya N., Kubota A., Kondo A., Hirano S., Saito A., Ohshima S., 2006, *Physica C: Superconductivity and its applications*, 445, 994

Sing S.L., An J., Yeong W.Y., Wiria F.E., 2015, *Journal of Orthopaedic Research*,

Sing S.L., Yeong W.Y., Wiria F.E., 2016, *Journal of Alloys and Compounds*, 660, 461

Singh I., Tripathi D.V., 2011, *Int. J. Comp. Tech. Appl*, 2, 1595

Su W., Cook B., Tentzeris M., Mariotti C., Roselli L., 2014, *Antennas and Propagation Society International Symposium (APSURSI)*, 2014 IEEE. IEEE, p. 858

Tiercelin N., Coquet P., Sauleau R., Senez V., Fujita H., 2006, *Journal of Micromechanics and Microengineering*, 16, 2389

Tong K.-F., Fortuny C.B., Bai J., 2015, *2015 International Symposium on Antennas and Propagation (ISAP)*. IEEE, p. 1

Tong K., Li K., Matsui T., Izutsu M., 2001, *Antennas and Propagation Society International Symposium*, 2001. IEEE. IEEE, p. 406

Valmiro R., Kitaguti H., Barbin S., 2015, *2015 Asia-Pacific Microwave Conference (APMC)*. IEEE, p. 1

Wang S., Lee J.M., Yeong W.Y., 2015, *International Journal of Bioprinting*, 1

Workman E., Chang I., Noghianian S., 2015, *Electro/Information Technology (EIT), 2015 IEEE International Conference on*. IEEE, p. 569

Yeong W.-Y., Chua C.-K., Leong K.-F., Chandrasekaran M., Lee M.-W., 2005, *Virtual modelling and rapid manufacturing-advanced research in virtual and rapid prototyping*, 115

Yeong W., Yap C., Mapar M., Chua C., 2013, *High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping: Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping*, Leiria, Portugal, 1-5 October, 2013. CRC Press, p. 65

Zhu H., Narakathu B.B., Fang Z., Aijazi A.T., Joyce M., Atashbar M., Hu L., 2014, *Nanoscale*, 6, 9110