

## Research Article

# Development of Novel Nano-Silver-Based Antenna for Green Agriculture

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The designed antenna is a monopole Z-shaped antenna operating in an unlicensed band of 2.4 GHz fabricated using low cost inkjet printing technology. The proposed inkjet printing technology is eco-friendly since the material used here is an ordinary “paper” that is suitable for the green technology. The conducting patch of silver nanoparticle (AgNP) ink has very high conductivity 35,700,000 S/m and instant curing property which helps in fabrication process without UV curing or oven heating. The printer used also is the cheap home printer HP DJ 2130 rather than the expensive Brother and Epson printers used in previous works. The printed antenna will be helpful in conditions to ascertain its performance in green agriculture in the form of RF-ID sensors, soil pH value sensor, and moisture sensor. The proposed antenna attains the gain of 2.5 dBi at the ISM band of 2.4 GHz with optimal VSWR value between 1 and 2 over the desired frequency band. The directivity and radiation efficiency of the proposed antenna are 2 dBi and 80%, respectively. The overall cost of the proposed antenna is much lesser in the order of 10 times than the recent low cost design.

## 1. Introduction

Green agriculture is the revolution of Indian agriculture that addresses the problems such as land pollution, biodiversity, and climate change. The land preservation can be done by controlling the addition of pollutants into the soil. Fertilizers, nonbiodegradable waste, and e-waste are the causes of land pollution. The quality and quantity of such pollutants need to be measured for the upgradation of soil property. In our country, for strengthening the high biodiversity areas, the transformation of agricultural systems is highly essential. To catalyze transformation in agricultural sector, more concentration towards the sustainable

landscape management is needed. Land is a vital resource to humankind, like air and water. Land degradation is the deterioration or loss of the productive capacity of the soils for the present and future. This is a global challenge that affects everyone through food insecurity, higher food prices, climate change, environmental hazards, and the loss of biodiversity and ecosystem services. Land pollution is happening at an alarming pace, contributing to a dramatic decline in the productivity of croplands and rangelands worldwide [1–3]. Hence, rapid remedial action is essential for developing green agriculture system in our country. Hence, an array of antennas that acts as a sensor for measuring various on-field parameters of the agricultural

land is required to facilitate the easiness and readiness of farmers before cultivation. The proposed irrigation antenna module serves as a means of supporting the farmers by monitoring soil qualities such as chemical property (pH value, organic content), fertility, moisture, and environmental properties such as rainfall, humidity, temperature, and motion. Irrigation antennas can be deployed with leafs, automatic sprinkler systems, and pumps and in cultivation machines. Wireless sensors need to be deployed over the fields to enable farmers for easy monitoring of the current field status and prediction of the crop status. The deployment of wireless antenna modules which serve as sensors of various environmental and chemical parameters help in eliminating long runs of copper cables around the farms which are unsafe, difficult to implement, and costly [4, 5].

The technology more suitable here for developing the agricultural network antenna is the inkjet printing technology which is highly economic and supports mass production. Inkjet printing is a technology that is used mainly in pattern making. This method is widely accepted for variety of applications as it is highly environment friendly, cheap, and flexible [6–9] with all kinds of substrates such as paper, silicon, and mica sheets. The usual process of antenna fabrication involves masking and etching operations which are both time and cost consuming. But, this printing technology is a direct writing method that jets the conductive ink droplets directly on the substrates using an ordinary office printer. The inkjet printing methodologies for printing a Z-shaped monopole CPW fed antenna is being discussed here.

Inkjet printed Z-shaped CPW monopole antenna is designed at the frequency of 904.5 MHz in [6] using Dimatix DMP-2800 Series printer by jetting silver nanoink on ordinary paper substrate. There are many reasons for choosing paper as the substrate as it is an excellent candidate at low cost for RF-ID and RF applications [10, 11]. In the work of [12], the similar monopole CPW Z-shaped antenna is designed at 1.57 GHz on glossy paper using silver nanoink of viscosity 2.30 mPa s and surface tension of 32 mN/m. The printer used in this work is Fujifilm Dimatix 2800 and offers maximum gain of 1.67 dB. In the above two works, the printed antenna requires postsynthesis annealing for higher conductivity of nanoink. One another drawback of the above works is that the printer used for the designs are very expensive in the order of ₹20,00,000. The recently proposed antenna design in [13, 14], printed on PET substrate at the ISM band of 2.4 GHz, is curing free and also uses much cheaper office printer in comparison with the Dimatix printer used in the earlier works. The previous works on inkjet printed antennas made prints with expensive Brother and Epson printers [15]. These printers are equipped with special, detachable ink tanks of huge storage capacity that requires more ink to be filled that makes the process costlier.

The objective of the proposed work is to design the printable antenna using much cheaper printer preferable to be used with low quantity of ink. The printer used in the proposed design is cheaper than the recent low-cost office

printer used in [16] and also the printer head is thermal, whereas the printer head used in other previous literatures used much expensive piezo-electric head printers. Moreover, the proposed printing design uses nanoink whose conductivity is in the order of  $3.57 \times 10^7$  S/m that is nearly 4 times higher than the silver NP (nanoparticle) ink used in the recent work [13]. The AgNP used here has the instant curing capacity that avoids the sintering/annealing process. Thus, the curing-free, low-cost AgNP ink suitable for thermal head-based highly inexpensive HP home printer-based design methodology is explained in this paper.

The remainder of this paper is organized as follows: Section 2 discusses on the design of monopole antenna element and its validation in CST-MWS tool, Section 3 focuses the fabrication of this antenna in eco-friendly inkjet printing process, and the scope of this antenna in green agriculture is presented in Section 4.

## 2. Design of Z-Shaped Monopole Microstrip Patch Antenna

Microstrip patch antenna is the popular printed antenna that plays a significant role in all applications due to its ease of fabrication, low cost, and flexibility with other circuit elements [17]. The compact patch antenna consists of a conductive plate over the substrate of dielectric. This is highly preferred over the other antennas specifically for wireless applications due to its compact planar structure that can be easily fixed over leaf or stem or conformal over the surface of any object. The shape and dimension of the antenna decide the frequency of operation of the antenna.

The performances of the antenna such as wider bandwidth, higher resolution, and better radiation are all enhanced by choosing substrates with low dielectric constant (less than 6) that leads to larger antenna dimension. Hence, another easy way of enhancing the antenna performance is inserting slots to perturb the flow of current. This current perturbation helps to increase the BW in comparison with the conventional patch by diverting the current direction. The following section explains the design steps of the Z-shaped microstrip patch antenna as pointed out in [18]. Figure 1 depicts the configuration of the Z-shaped patch antenna element. The dimensions of the above design are calculated in accordance with the centre of frequency ( $f_0$ ) and hence the wavelength ( $\lambda_0$ ). The patch which is rectangular in shape has the width ( $W$ ) and length ( $L$ ) as the major dimensions. This is according to software description. Two slot lengths are approximately equal to width of the patch ( $w$ ) and placed symmetrically in the XY plane from the patch radiator with slot width  $L_1$ . Initially, the length  $L$  and width  $W$  of the patch radiator having substrate of dielectric constant  $\epsilon_r$  and thickness  $h$  are calculated as given in the steps below. These steps involve the calculation width ( $W$ ), effective dielectric constant ( $\epsilon_{\text{reff}}$ ), and change in dimension ( $\sqrt{L}$ ) due to the fringing effects between the patch and the substrate.

Step 1: calculation of width is done using the following equation:

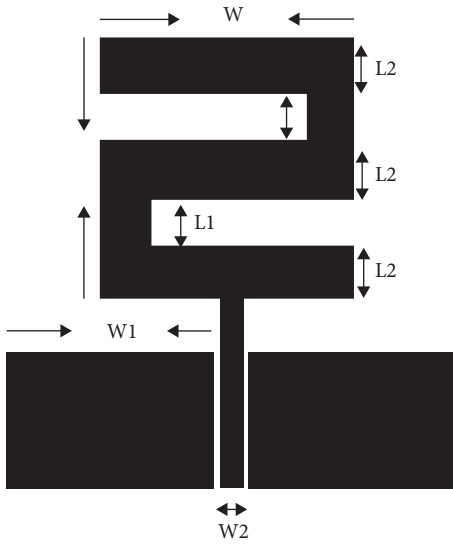


FIGURE 1: Configuration of Z-shaped microstrip patch antenna.

$$W = \frac{c}{2f_0} \left( \sqrt{\frac{2}{1 + \epsilon_r}} \right), \quad (1)$$

where  $\epsilon_r$  is the dielectric constant of the substrate and  $c$  is the velocity of EM wave in free space ( $3 \times 10^8$ ).

Step 2: calculation of effective dielectric constant is by using the following equation:

$$\epsilon_{\text{reff}} = \frac{1 + \epsilon_r}{2} + \frac{\epsilon_r - 1}{2} \left( 1 + 12 \frac{h}{W} \right)^{-(1/2)}. \quad (2)$$

Step 3: calculation of change in dimension is indicated as in the following equation:

$$\nabla L = 0.412h \frac{(\epsilon_{\text{reff}} + 0.3)((W/h) + 0.26)}{(\epsilon_{\text{reff}} - 0.26)((W/h) + 0.8)}. \quad (3)$$

Step 4: calculation of length of the patch is as defined in the following equation:

$$L = \frac{c}{2f_0 \sqrt{\epsilon_{\text{reff}}}} - 2\nabla L. \quad (4)$$

For our proposed antenna element chosen with the ordinary “paper” as the substrate having dielectric constant = 2.31, operating at the frequency of  $f_0 = 2.4$  GHz, the dimensions calculated using equations (1)–(4) are given in Figure 2, so as to insert two slotted sections symmetrically with respect to the centre, the thickness of the Z-element is chosen as  $L_2 = 9$  mm and  $L_1 = 6.85$  mm such that the total length  $3L_2 + 2L_1 = L = 40.9$  mm. Figure 3 shows the design of Z-shaped microstrip patch antenna using Ansys HFSS antenna design tool with the theoretical calculations obtained above. Figure 4 shows the reflection coefficient of the proposed design with simulation and experimental results that almost match. The obtained results show that they are well below the required threshold of  $-10$  dB at the operating

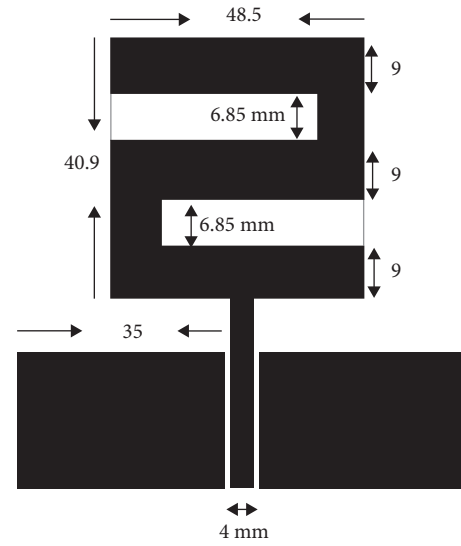


FIGURE 2: CPW monopole element design.

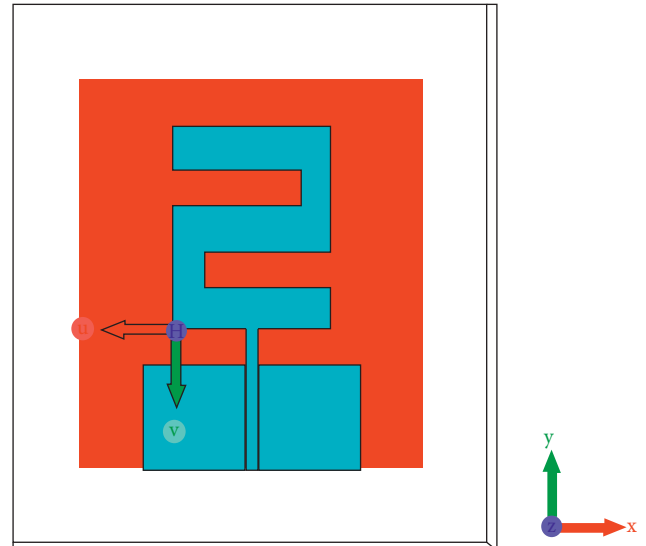


FIGURE 3: Z-shaped monopole element design using Antenna Design tool.

frequency of 2.4 GHz. This is the unlicensed frequency band typically used for the agricultural applications worldwide. Figure 5 shows the VSWR characteristics of the designed antenna and is attaining the optimal value in the band of interest. Figures 6 and 7 show the directivity and gain of 3 D plots that show the gain and directivity of 2 dBi and 2.5 dBi, respectively.

### 3. Inkjet Printing of Monopole Microstrip Patch Antenna

The inkjet printing is the extremely inexpensive, direct writing method that jets the ink droplets directly on the substrates. The substrate chosen for the antenna must be compatible with the printer and the ink used to fabricate the radiator patch on the chosen substrate must be flow-free

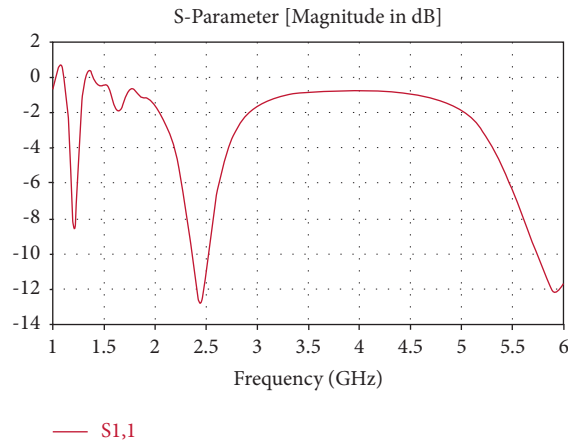


FIGURE 4: Reflection coefficient of the proposed design.

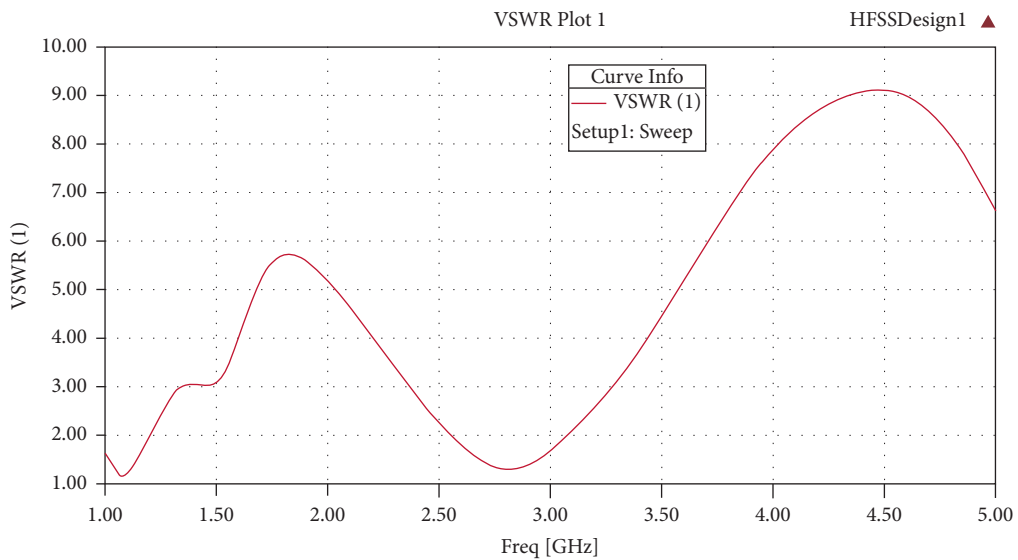


FIGURE 5: VSWR coefficient of the proposed design.

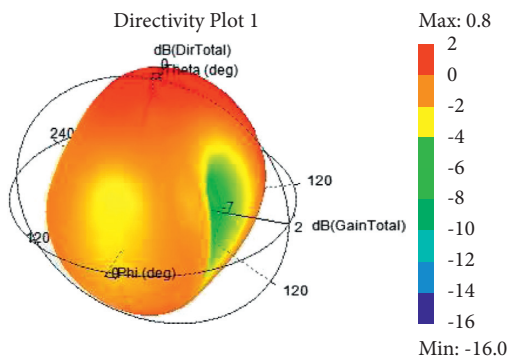


FIGURE 6: Directivity plot of the proposed design.

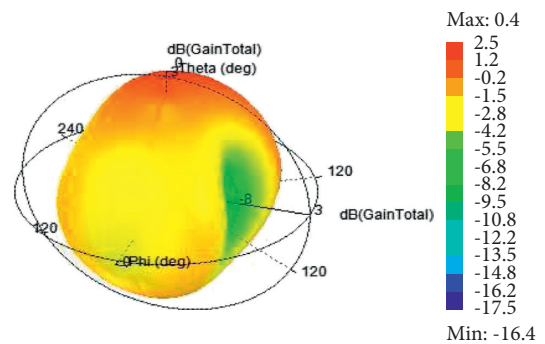


FIGURE 7: Gain plot of the proposed design.

from the printer nozzle. Hence, the selection of printer that suits for the substrate and the ink plays a major role in this inkjet printing technology. The proposed design uses only commercially available desktop inkjet printer that can be operated by refilling the single black and white cartridge.

After taking the printouts, the printed antenna needs to undergo the curing process in order to raise the conductivity of the radiator patch to a specific value. Traditional methods of curing involve oven heating, exposure to UV, etc. But, the ink used in the proposed technique requires no curing since

it supports instant curing which is the additional benefit of this work.

Hence, the principal parameters that decide the quality of fabrication in inkjet printing are the substrate properties such as thickness and dielectric constant, resistivity of conductive ink, printer cost, and challenges in curing process as shown in Table 1. The process of inkjet printing of the designed monopole antenna is briefed in the upcoming Sections 3.1 and 3.2.

**3.1. Proposed Low-Cost Inkjet Printing.** This section explains the process of the proposed low-cost inkjet printing for the antenna fabrication. The proposed design makes use of relatively inexpensive ordinary “paper” as substrate and curing-free “silver nanoparticle ink” as the conductive ink. In order to take the printouts, initially the cartridge HP 302 shown in Figure 8 is filled with the nanoparticle ink using the syringe. The printer used in the proposed fabrication process is the readily available, extremely low-cost, thermal head-based HP printer.

The work [15] demonstrates various examples of inkjet printed antennas fabricated by using conductive silver ink on photograph paper substrates. The printed antenna design proposed in this paper makes use of curing-free “silver nanoink.” The substrate used is the commercially available, low-cost, ordinary “paper” as the substrate material. The A4 size “paper” of 75 GSM having average thickness of approximately 0.1 mm is preferred. But, the earlier works on inkjet printed antenna used comparatively costlier dielectric materials like mica sheets and glossy papers as the substrates. Hence, the material chosen in the proposed design costs very low of less than ₹0.50 per paper and compatible with all types of printers as the thickness of the paper is also very less (<0.1 mm). The glossy paper can be used in place of “ordinary paper” as substrate to improve the durability of substrate.

The conductive ink used for fabricating the patch radiator is the silver nanoparticle ink NS6130-10-1300-Ag, 99.9%, APS (average particle size) 30–100 nm. The ink is the silver nanoparticle ink of viscosity of 8 Cp and surface tension of minimum 30 dyne/cm that helps to control the ejection of ink droplets from the nozzle. Selection of proper sintering process is the bottleneck of nanoink as mentioned in [17, 19]. One of the main reasons for selecting the nanoparticle-based ink is the possibility of sintering at extremely low temperatures and resistivity against oxidation. Hence, this ink is suitable for printers with thermal heads (HP printers) as they easily melt at low temperature compared to bulk inks. This avoids the use of expensive printers with piezo-electric heads (Brother and Epson printers) which are used in the literatures [10, 20, 21]. Another property of the ink is the resistivity against oxidation that helps to prevent the ink being clogged in the printer heads. Hence, this ink is more suitable for printers with thermal heads (HP printers) as they easily melt at low temperature compared to bulk inks. This ink is also suitable for all types of printers, but the ink used in previous literatures used only printers with piezo-electric heads which are expensive Brother and Epson printers.

TABLE 1: Properties of ink and substrate.

"Ink" properties	
Viscosity	8 Cp
Surface tension	35 mn/m
Conductivity	35,700,000 s/m
Linear formula	Ag
Molecular weight	107.87 g/mol
Storage temperature	2–8°C
Thermal expansion	18.9 $\mu\text{m}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$ (25°C)
Particle size	30–100 nm
Surface tension	30–32 dyne/cm
Density	1.22 g/mL at 25°C
Boiling point	2162°C
Young's modulus	83 GPa
Bulk density	0.312 g/cm <sup>3</sup>
Solvent	Water-based or organic
"Substrate" properties	
Relative permittivity	4.01
Loss tangent	0.07
Dielectric constant	2.31
Thickness	0.1 mm



FIGURE 8: HP 302 cartridge filled with nanoparticle ink NS6130-10-1300 using ordinary medical syringe.

The previous works on inkjet printed antennas made prints with expensive Brother and Epson printers. These printers are equipped with special, detachable ink tanks that are refillable using the preferable conductive inks. But, the drawback of this ink tank attached printers are that they need huge quantity of ink to fill the tanks and so large amount of conductive inks are required (minimum of 25 mL in each of the three cartridges). Another drawback of these printers is the difficulty of reusing the ink after some time as the inks get clogged with the printer heads, spoiling the whole printer system. The printer used in the proposed design is the much cheaper, readily available one that uses single BW cartridge that occupies only a minimal ink quantity (less than 10 mL). The printer used for printing is HP DJ 2130 series printer that uses easily refillable cartridges.





FIGURE 9: Printing of Z-shaped monopole antenna on paper using HP DJ 3120 printer.

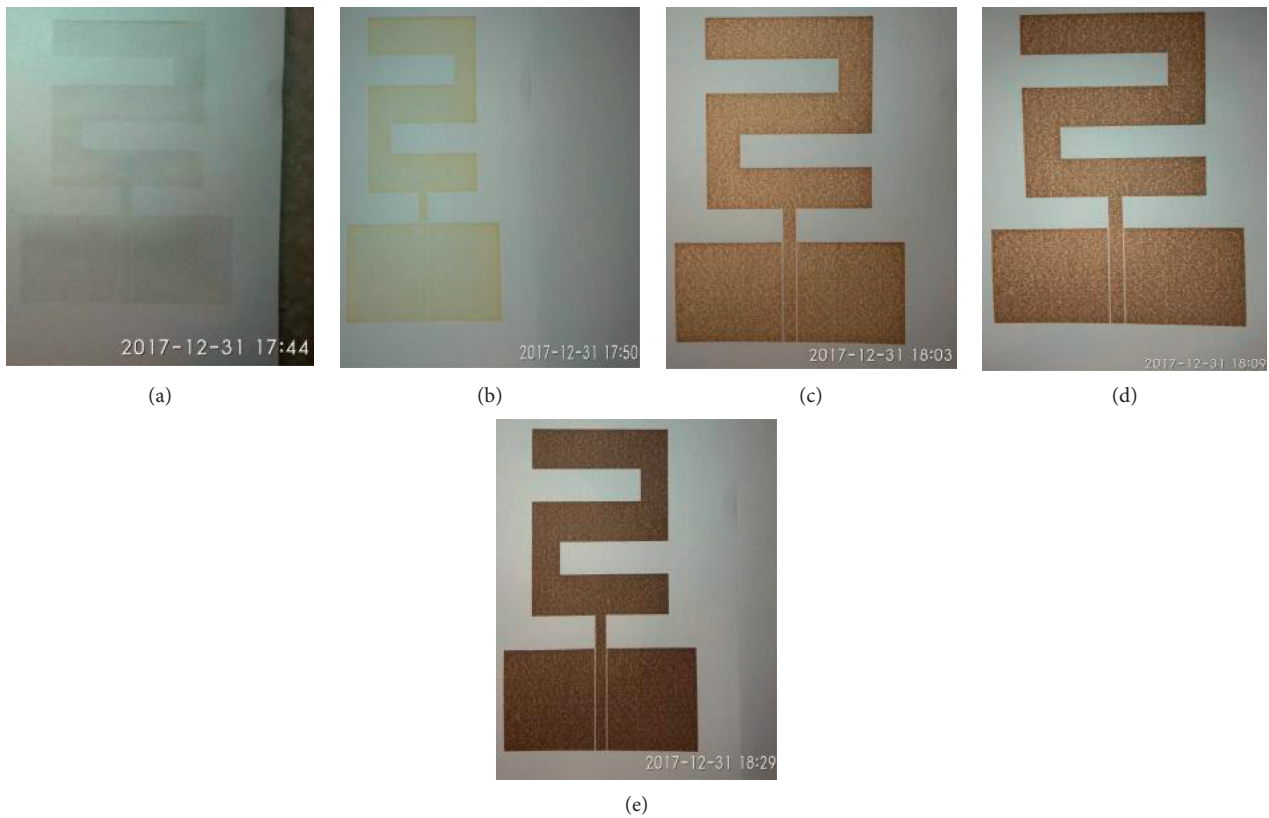


FIGURE 10: Curing of inkjet printing antenna at different time instants: (a) at time 17.44, (b) at time 17.50, (c) at time 18.03, (d) at time 18.09, and (e) at time 18.29.

TABLE 2: Conductivity Vs time of AgNP at room temperature.

Time (msecs)	Resistance (ohms/cm)
0	10 M
5	9
10	5
15	4.2
25	3.9
40	2.1
45	2

TABLE 3: Comparison of the proposed design and the recent works.

Parameters	[6]	[12]	[13]	[15]	Proposed design
Printer used	Dimatix printer 2800 series	Dimatix printer 2800 series	Office printer	Epson C88+	HP DJ 2130 printer
Printer head	Piezo-electric	Piezo-electric	Piezo-electric	Piezo-electric	Thermal head
Cost of the printer	Very expensive ₹20,00,000	Very expensive ₹20,00,000	Cheap ₹42,000	Expensive ₹1,00,000	Very cheap ₹3,000
Resonant frequency	904.5 MHz	1.57 GHz	2.45 GHz	—	2.4 GHz
Conductivity of ink	$4 \times 10^6$ S/m	$1.6 \times 10^6$ S/m	$1.11 \times 10^7$ S/m	—	$3.57 \times 10^7$ S/m
Substrate used	Normal paper	Glossy paper	PET	Photo paper	Normal paper
Cost of the ink	Expensive >70000	Expensive >70000	Cheap <30000	—	Cheap <3000
Postprocessing	Annealing processes for 10 hrs in an expensive industrial oven heating	Annealing processes for 4 hrs in an expensive industrial oven heating	Not required	Annealing processes for 90 mins in a commercial oven heating	Not required
Preheating	Heating vacuumed platen up to 60°C	Heating vacuumed platen up to 60°C	Not required	Not required	Not required
Annealing temperature	100	180	Not required	160°C–170°C	Not required
Gain	—	1.67 dB	1.44 dBi	—	2 dBi

The cost of this printer is not more than ₹3000 along with the use-and-throw cartridges. Figure 8 shows the ordinary medical syringe used for filling up the single BW cartridge of the HP DJ 2130 printer. The printing process is depicted in Figure 9.

### 3.2. Design Steps of Antenna Fabrication Using Inkjet Printing.

The fabrication of antenna using a readily available paper, curing-free silver nanoink, and cheap office printer is summarized as follows:

- (i) Antenna design is simulated using CST-MWS tool. The simulated designs are converted to Gerber file format.
- (ii) HP DJ 2130 printer is connected to the computer where the designs are stored in Gerber file format.
- (iii) The HP 302 BW cartridge compatible with the abovementioned printer needs to be empty with no more ink left inside.
- (iv) The syringe is first filled with the silver nanoparticle ink NS6130-10-1300.
- (v) Using the syringe, the cartridge is injected with 10 mL of ink.
- (vi) The JK Copier 75 GSM A4 size paper is fed in the input tray of the printer. In the printer settings, the “paper type” is chosen as “Plain paper.”
- (vii) After taking the prints, the print heads are cleaned with alcoholic wipes to avoid clogging of ink over the print heads. This prevents the cartridges getting damaged due to ink deposition.
- (viii) Once the process is completed, the cartridge is removed and stored in the refrigerators if the ink is left over. If this is not done, the chemical property of the ink may change. This is due to the reaction between the thermal head of the HP printer and the ink.
- (ix) The final step of fabrication is the curing process due to which the resistivity of the patch radiator decreases. The ink chosen here does not require separate curing process and hence by simply keeping the antenna at room temperature of around 28°C obtains the maximum conductivity in 45 minutes.
- (x) This curing process can be accelerated and maximum conductivity is reached in less than 5 minutes time if the printed design is exposed to sunlight (around 30–34°C).

- (xi) The cured antenna samples are connected with SMA connector by simply applying physical pressure and then the characteristics are measured using network analyzer.

**3.3. Curing of Inkjet Printing.** Curing is the final stage of antenna fabrication in inkjet printing technology. Curing process helps to increase the conductivity of the patch since thermal agitation mobilizes the electrons present in the heated patch radiator. Curing also removes excess solvent and provides uniformity by providing connectivity between the particles. In the process of curing, the uniformity is increased which plays a major role in inkjet printing. Traditional curing method used in the previous literature [15] used commercially available ovens to heat the printed antennas for about 90 minutes.

The resistance of the printed element is in the order of few k $\Omega$ s immediately after printing, whereas it reduces to the order of few  $\Omega$ s after curing. The time and temperature of curing determine the conductivity of the patch. In our proposed design, no such technique is needed for curing. The silver nanoparticle ink used in our design instantly cures while exposing to sunlight (30–34°C). Without sunlight, the conductive traces are allowed to attain the maximum conductivity by keeping the printed traces of design in room temperature (28°C) for about 90 minutes. Figures 10(a)–10(e) show the curing process at different time instants from the time the printout is taken (time stamp is attached in each picture).

From Figures 10(a)–10(e), it is clear that as the time progresses, the darkness of the conducting surface increases which shows that the conductivity increases. This is done without using any additional curing process and allowing to simply resting at room temperature of around 28°C. It is noticed that the maximum time needed for curing is 45 minutes from the time of taking printout at IST 17.43 and the final maximum conductivity at IST 18.29, as shown in Figure 10(e). Table 2 provides the variation in resistivity with respect to time at room temperature measured at 1 cm length of the conductive strip. Table 3 summarises the recent works on inkjet printing of Z-shaped antenna and performance is analysed. The AgNP used here has the instant curing capacity that avoids the sintering/annealing process. Thus, the curing-free, low-cost AgNP ink suitable for thermal head-based highly inexpensive HP home printer-based design methodology is designed and analysed in this work. This can be further modified to be used in other wireless applications as this work achieves higher gain in comparison with other similar works [22].

## 4. Conclusion

The single Z-shaped monopole element printed using “inkjet” printing technology uses relatively inexpensive desktop inkjet printer and ordinary “paper” as the substrate material. The ink chosen for the patch has the chemical properties which allow instant curing, whereas the ink used in the previous works used the most complex oven heating

or electrical curing. Thus, the proposed antenna design is superior in all aspects. Additionally, there are many types of papers such as porous, hydrophobic, and semitransparent papers. The hydrophilic property is very useful in implementing sensors for rainfall, fog, and humidity measurement on leafs and surface of soils. Hence, the future focus of this work is to design antenna on various materials like this and analysing them in various climatic and soil conditions. In addition to this, implementation of array structures using inkjet printing is the future work to be carried out in near future for high gain applications in the areas where there is huge terrestrial loss.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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