RESEARCH ARTICLE

A Novel Approach for Production Challenges of Flexible Microstrip Patch AntennaHilal Koc Polat^a, Mirac Dilruba Geyikoglu^b, Bulent Cavusoglu^b and Mehmet Ertugrul^b*a Department of Electrical and Electronics Engineering, Erzurum Technical University, Erzurum, Turkey**b Department of Electrical and Electronics Engineering, Ataturk University, Erzurum, Turkey***Abstract**

It is unavoidable to decrease the thickness of the substrate in order to obtain enough flexibility. Decreasing the height of the substrate lowers the gain of antenna and its bandwidth. Thus, it is challenging to provide operability for the flexible materials and it requires new approaches. This paper is shown that the using nano silver paste for the designed antenna causes better return loss rates (S_{11}) and bandwidth. Also, the effect of sintering temperatures on the response of the antenna is analyzed for the range of 150 ° C to 350 ° C. The highest resonance frequency and the lowest return loss are observed at 350 ° C in this range. The SEM images of the antenna surfaces show that the nanoparticles in the paste group together with increasing sintering temperatures. When compared to the perfect conductor silver, better return loss and bandwidth are obtained.

*Keywords: Patch antenna, silver paste, flexible, IoT, sintering***1.Introduction**

The demand is increasing for the novel antenna approaches to meet the frequency and application variability requirements for the realization the Internet of Things (IoT). Some important design requirements include flexibility for wearable technologies, wide bandwidth and operability at allowed operating frequencies. Microstrip patch antennas are preferable due to its low cost and hassle-free production process. In order to make the production process even easier we use screen printing technique in this paper. The efficient, low profile, and easy-to-produce microstrip antennas are good candidates to provide high performance, reliable and interference-free communication for IoT applications. 5G brings many developments for the realization the Internet of Things (IoT). The available spectrum used in the communication systems is below 6 GHz [1]. However, the frequency ranges of 3.4-3.8 GHz, 4.4-4.9 GHz, 3.5-5.2 GHz are also expected to be used for 5G [2-4]. The microstrip patch antenna used in wireless communication are becoming increasingly important together with developing technologies. It is generally preferred due to its features such as being easy-to-produce, low cost and low profile. The patch antenna usually is a four-part design (patch, substrate, ground and feed). The substrate of the microstrip antennas is used to provide mechanical support and suitable gate between patch and ground plane. If the antenna is planned to be used on a variable shaped structure, either the antenna substrate is produced to fit the shape [5] or a flexible substrate produced from flexible materials is used [6, 7]. The microstrip patch antennas on the flexible substrates have been widely used in industrial, scientific and biomedical applications. Since the produced antennas need to be flexible and be suitable for bends, it is desired to make the substrate layer as thin as possible to allow better flexibility.

It should be noted that decreasing the substrate thickness decreases the bandwidth and gain of the microstrip patch antenna [8]. Then it becomes very important to improve the performance of the antenna in terms of return loss, bandwidth and gain by overcoming this disadvantage. In this paper, we introduce a new approach by using a silver-paste with nano particles as a conductive material to have a flexible yet operable antenna with a thin substrate layer. The silver-paste used has discontinued structure. This structure includes nano-silver and gaps among them. Due to this structure additional capacitive effects are obtained on the conductive surface which cause better conservation of the energy within the surface. This structure decreases the electromagnetic energy goes into the slab in which eventually causes surface waves. In this study a silver paste microstrip patch antenna is designed to operate between 4.4-4.9 GHz frequency band. Also, three different antennas are designed and fabricated in order to provide necessary comparisons to put forward the superiority of the silver paste patch antenna. One of the antennas is designed on FR4 by using copper patch. The FR4 substrate which has higher dielectric constant than kapton substrate does not have flexibility and fabricated only for comparison purposes. A good bandwidth and relatively low return loss can be achieved with this material. However, the fact that this material does not have a flexible structure narrows its application area. Another antenna fabricated is designed on kapton substrate using copper patch instead. It is also observed that increasing the height of the Kapton substrate has improved the bandwidth and reduced the loss of return. However, increasing the substrate's thickness reduces the flexibility of the material. The last antenna produced is the proposed antenna of this study which is designed on Kapton substrate by using nano-silver paste as the patch material. It is observed that higher bandwidth and better return loss is obtained compared to perfect conductor patch (copper or silver) in this case.

*Corresponding Author: hilal.koc@erzurum.edu.tr (H. KOC POLAT)

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2. Antenna Design and Fabrication

2.1. Basic design parameters

In order to give a complete view of the design issues we visit the basic design parameters of the patch antenna first.

Dielectric constant of the substrate is one of the parameters that determines size of antenna. When the transmission line model is used, the dimensions of the antenna are determined as follows for the desired resonance frequency (f_r), height (h) and dielectric constant (ϵ_r) [9].

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r + 1}} = \frac{\vartheta_0}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

Equation (1) is used to find the patch width (W) of the antenna. Here, ϑ_0 is the free space speed of the light. μ_0 and ϵ_0 represent magnetic and electrical permittivity of free space, respectively. ϵ_r is the dielectric constant of the antenna substrate.

If, $\frac{W}{h} > 1$ the effective dielectric constant is determined by (2).

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \quad (2)$$

The actual length of the patch (L) is calculated using (3-4).

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{W}{h} + 0.8 \right)} \quad (3)$$

$$L = \frac{1}{2f_r\sqrt{\epsilon_{eff}\mu_0\epsilon_0}} - 2\Delta L \quad (4)$$

The suitable ground size for the microstrip antenna is calculated by (5-6) [10].

$$L_g = L + 6h \quad (5)$$

$$W_g = W + 6h \quad (6)$$

Where L_g is the length and W_g the width of the ground patch. The impedance value of the rectangular microstrip patch (Z_a) is calculated by (7).

$$Z_a = 90 \frac{\epsilon_r^2}{\epsilon_r - 1} \left(\frac{L}{W} \right)^2 \quad (7)$$

Impedance matching between the feed and antenna patch is an important issue to obtain good return loss values. If the feed length is selected as the quarter wavelength, the characteristic impedance of the feed line can be calculated by (8) which meets the impedance matching requirement[11].

$$Z_0 = \sqrt{Z_{in}Z_a} \quad (8)$$

If $\frac{W}{h} \leq 1$,

$$Z_0 = \frac{60}{\sqrt{\epsilon_{eff}}} \ln \left[\frac{8h}{W_0} + \frac{W_0}{4h} \right] \quad (9)$$

If $\frac{W}{h} > 1$,

$$Z_0 = \frac{120\pi}{\sqrt{\epsilon_{eff}} \left[\frac{W_0}{h} + 1.393 + 0.667 \ln \left(\frac{W_0}{h} + 1.444 \right) \right]} \quad (10)$$

Where Z_0 is the characteristic impedance of the feed line, W_0 is width of the feed line. Through (9-10) a suitable W_0 is determined.

2.2. Design challenge issues

The designed antenna is desired to have the following properties,

- Thin and flexible substrate to obtain good flexibility
- Good return loss (low S11 parameter)
- High bandwidth
- Operation frequency for 5G
- Easy production

The main design challenge comes from decreasing the substrate thickness. It causes the bandwidth of the antenna to decrease due to the decreased reactive power related with the dielectric substrate thickness. It should also be noted that decreasing the substrate thickness causes better return loss (lower S11) and this is mainly due to the fact that the amount of energy propagates as surface wave decreases proportionally with the substrate's thickness. It is necessary to resolve the bandwidth issue in order to make this flexible material usable. The idea of this paper is to introduce and analyze the effects of a different patch material and see if a good operable antenna can be obtained. Making changes on the conductive patch tissue of the antenna, it is possible to change its radio frequency electromagnetic properties.

The antennas designed on the FR4 and planar kapton polyimide substrates using transmission line model are shown in Figure 1. Kapton polyimide film ($\epsilon_r = 3.5$) is a flexible material with a low loss factor over a wide frequency ($\tan \delta = 0.0026$) is chosen as an antenna substrate due to the good balance of physical, chemical and electrical properties. Moreover, kapton polyimide is very robust with a very low profile (125 μm), a tensile strength of 165 MPa at 73 ° F, a dielectric strength of 3500-7000 vol/mil and a temperature range of -65 to 150 ° C. The calculated results for the electrical dimensions of the 4.65 GHz antennas are presented in Table 1. Since the dielectric constant of FR4 is greater than kapton, the size of FR4 based antenna is smaller than kapton based antenna (see (1-6)).

Figure 1. Geometry of the designed planar antennas at 4.65 GHz, (a) Kapton substrate- silver patch, (b) FR4 substrate- copper patch

Table 1. Design parameters of the microstrip patch antenna

	FR4 (Copper patch)	Kapton (Silver Paste)
$f_0(\text{GHz})$	4.65	4.65
ϵ_r	4.3	3.3
$h(\text{mm})$	1.3	0.125
$L(\text{mm})$	15.0	17.23
$W(\text{mm})$	19.6	21.51
$L_g(\text{mm})$	22.8	17.98
$W_g(\text{mm})$	27.4	22.26

The silver conductive patch on the Kapton substrate is designed as a continuous conductor in a simulation environment. During production process, silver paste (nano-material textured surface) is laid on kapton using screen printing technique. Thanks to this technique, the fabricated of silver paste microstrip patch antennas have been easily facilitated. Following the screen printing, sintering process is applied. Firstly, the printed patterns are dried at 120 ° C for 20 min. to remove solvent in silver paste. Secondly, they are placed at convection oven at sintering temperatures ranging from 150 ° C to 350 ° C temperatures, which are below the melting point of Kapton substrate. The individual antennas are heated at five different temperatures, 150-200-250-300-350 ° C, and exposed to argon %5 hydrogen for 15 min at these temperatures. The structures are then cooled at room temperature. Then, a copper tape is used as the antenna ground underneath the structure. Finally, it is ensured that the SMA connector is attached to the fabricated antenna well. The pictures of the fabricated microstrip patch antennas are shown in Figure 2.

Figure 2. Picture of the fabricated planar antennas at 4.65 GHz with different materials, (a) FR4 substrate- copper patch top and bottom views, (b) Kapton substrate- copper patch side, top and bottom views, (c) Kapton substrate- silver paste top and bottom views.

2.3. Screen printing technique

The conventional technique for the antenna design includes etching the metal using a photolithographic process, which requires removing the metal in order to form the patch design. This process is considered wasteful, since it requires large amounts of chemicals and energy and produce waste material. However, screen printing is a relatively new area of research and development in electronics manufacturing (Figure 3). In this technique, metallic particles are blended into an ink, which is applied onto the substrate. In the dried ink, the metal particles touch and overlap each other to get continuous conductive traces. Screen-printing is one of the easiest, cheapest and flexible fabrication technique for many applications such as antenna, RF ID, sensors etc. It is possible to fabricate almost any design on many substrates such as paper, textiles, plastics, ceramics, wood, glass, metal etc. using printing techniques [12]. This technique is also cheaper and more environmentally friendly than the conventional technique. Screen printing technique requires conductive ink or paste for the patch fabrication. Silver paint is one of the best material among conductive pastes or inks for the printed electronics. If the conductivity of the printed area and thickness are high enough, the performance of the antenna is the same as the copper foil antenna [13]. But, the thickness of the conductive layer should be several times greater than the skin depth. According to [13], the printed thickness of 5.5 μm should be enough to produce optimum return loss performance. Conductive silver-based antennas provide a performance similar to that of its copper equivalent [14]. Since bandwidth of the antenna increases due to increased surface resistivity [15], silver paste based antennas have larger bandwidth than the copper antennas for the same geometry.

Figure 3. Pattern transfer operation in screen printing technique

3. Results and Discussion

3.1. Comparison of simulation and measurement

The simulated reflection coefficients (S11) of the designed antennas with the FR4 and kapton substrates in CST Simulation Environment are shown in Figure 4. The figure shows that the antenna based on FR4 substrate with copper patch has 223 MHz bandwidth at 4.49 GHz resonance frequency, the antenna based on kapton substrate with copper patch has 30.2 MHz bandwidth at 4.59 GHz resonance frequency and the antenna based on kapton substrate with silver patch has 52.8 MHz bandwidth at 4.59 GHz resonance frequency. The silver patch antenna has a lower return loss. However it has better bandwidth than copper patch on kapton substrate.

The reflection coefficients of the simulated antennas with different kapton substrate thickness (h) are shown in Figure 5. It is observed that the antenna bandwidth increases and the return loss decreases as the thickness of the kapton substrate increases.

Figure 4. The reflection coefficients (S11) of the simulated antennas with different material

Figure 5. The reflection coefficients (S11) of the simulated antennas with different kapton substrate thicknesses (h)

The measured reflection coefficients (S11) of the fabricated antennas with the FR4 and kapton substrates are shown in Figure 6. The figure shows that the antenna based on FR4 substrate has 54.8 MHz bandwidth at 4.70 GHz resonance frequency, the antenna based on h=0.125 mm kapton substrate with copper patch has 103.3 MHz bandwidth at 4.99 GHz resonance frequency, the antenna based on h=1mm kapton substrate with copper patch has 117 MHz bandwidth at 4.89 GHz resonance frequency, and the antenna based on kapton substrate with silver patch has 149.9 MHz bandwidth at 5.38 GHz resonance frequency.

Figure 6. The measured reflection coefficients (S11) of the fabricated antennas with different material

The resonance frequency, bandwidth and return loss of the antennas obtained in simulation and measurements are presented in Table 2. When the measurement results are examined, it is seen that the kapton substrate has lower return loss and better bandwidth than FR4. These parameters can be further improved by increasing the thickness of the kapton. But, increasing the substrate thickness will adversely affect the flexible structure of the antenna. Furthermore, increasing the substrate thickness increases the surface wave stimulation. In this case, the radiation pattern of the antennas may

be disturbed and the efficiency may decrease. So, the thickness of the substrate can be increased to a certain extent.

Table 2. Resonant frequency and bandwidth of the simulated and fabricated antennas

Simulation			
Materials	Resonance Frequency (GHz)	Bandwidth (MHz)	Return Loss (dB)
FR4 (copper patch)	4.49	223	-23.35
h=0.125 mm Kapton (copper patch)	4.59	30.2	-11.19
h=1 mm Kapton (copper patch)	4.42	156	-12.28
h=0.125mm Kapton (silver patch)	4.59	52.8	-25.89
Measurement			
Materials	Resonance Frequency (GHz)	Bandwidth (MHz)	Return Loss (dB)
FR4 (copper patch)	4.7	54.8	-13.45
h=0.125 mm Kapton (copper patch)	4.99	103.3	-20.19
h=0.125mm Kapton (silver patch)	4.89	278	-21.12
Silver paste	5.38	149.9	-34.66

Figure 7 shows the radiation patterns of the designed antennas. The radiation patterns were examined according to the activity parameter as co-polarized and cross-polarized in the y-z plane. As can be seen, both in the E-plane and H-Plane, all of the antennas have omnidirectional radiation pattern. In addition, the cross-polarization radiation of the FR4 substrate- copper patch antenna is 8.7dB lower than the co-polarization radiation for the E-plane, and 8.7 dB lower for the co-polarization H-plane, whereas the antennas based on Kapton substrate are 10.1 dB lower for the E-plane and 10.1 dB lower for the H plane.

3.2. SEM analysis

The measured reflection coefficients (S11) of the fabricated antennas with different sintering temperatures are shown in Figure 8. The figure shows that the 150°C heated antenna has 176.9 MHz bandwidth at 5.01 GHz resonance frequency, the 200°C heated antenna has 193.8 MHz bandwidth at 5.08 GHz resonance frequency, the antenna 250°C heated has 192.2 MHz bandwidth at 5.2 GHz resonance frequency, the antenna 300°C heated has 172.8 MHz bandwidth at 5.24 GHz resonance frequency and the antenna 350°C heated has 148.6 MHz bandwidth at 5.38 GHz resonance frequency. The values shows that, as the temperature increases the resonance frequency is increased, the bandwidth has decreased and return loss has improved usually.

The increase in the resonance frequency can be explained by the growing pores of the silver paste with increasing temperature. Because, the increase in pore size means that the total size of the conductor is reduced. The pore sizes at different temperatures are shown in Figure 9.

Figure 7. Co-Polar and Cross Polar plots for the designed antennas, (a) FR4 substrate- Copper patch, (b) h=0.125mm Kapton substrate-Copper patch, (c) h=1mm Kapton substrate- Copper patch, (d) h=0.125mm Kapton substrate- Silver patch

Figure 8. The measured reflection coefficients (S11) of the fabricated antennas with different sintering temperatures.

Figure 9. FE-SEM images of silver paste patch at different sintering temperatures, (a) 120° C, (b) 150° C, (c) 200° C, (d) 250° C, (e) 300° C and (f) 350° C

4. Conclusion

Flexible patch antennas have many application areas, however it is necessary to decrease the thickness of the substrate layer in order to obtain enough flexibility. As it is shown decreasing the substrate height causes performance loss. In this study we have provided a new and novel approach for fabricating a flexible patch antenna. In the study, the disadvantage of thin layer of substrate were tried to overcome by using silver-paste as the patch material. Since the paste includes nanoparticles, it helps keeping the most of energy inside the patch till the end of the patch along with less power transferred to the layer just between the patch and substrate which is the source of surface waves. As a result it is shown that the using nano silver paste causes better return loss rates (S_{11}) and bandwidth. Also, it is observed that the higher the sintering temperature the better results obtained in terms of return loss (S_{11}). However, more shift on the resonance frequency and slight decrease in the bandwidth is observed after 200 ° C. When the SEM images of the antenna surfaces are analyzed it shows that the nanoparticles in the paste group together with increasing sintering temperatures and it is believed that this notion is the cause of the observed changes. The reflection coefficient parameters of simulation and measurement results of the microstrip antenna demonstrate fitness of the design.

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