Antenna array design on flexible substrate for wireless power transfer

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Abstract
Purpose – In this work, a microstrip antenna array for wireless power transfer (WPT) application is reported. The proposed 4 × 4 antenna array operating at 16 GHz is designed using a flexible Kapton polyimide substrate for a far-field charging unit (FFCU).

Design/methodology/approach – The proposed antenna is designed using the transmission line model on a flexible Kapton polyimide substrate. The finite element method (FEM) is used to perform the full-wave electromagnetic analysis of the proposed design.

Findings – The antenna offers −10 dB bandwidth of 240 MHz with beam width and broadside gain found to be 29.4° and 16.38 dB, respectively. Also, a very low cross-polarization level of −34.23 dB is achieved with a radiation efficiency of 36.67%. The array is capable of scanning −15° to +15° in both the elevation and azimuth planes.

Originality/value – The radiation characteristics achieved suggest that the flexible substrate antenna is suitable for wireless charging purposes.

Keywords Far-field charging unit (FFCU), Flexible substrate, Kapton polyimide, Microstrip array antenna, Phased-array, Wireless charging, Wireless power transfer (WPT)

Paper type Research paper

1. Introduction
With the advancement of mobile technology, devices such as wearables, tablets and smartphones get used for longer duration. With this development, it is necessary to keep the devices adequately charged all the times. Most of these devices do not require cords for data connectivity, however, charging still demands tying up these devices with a wire (Patil and Padaganur, 2018). The goal of wireless power is to remove these cables and wirelessly transmit power to charge these devices (Sharma, 2016; Heo et al., 2017). Wireless power transfer (WPT) is a generic term for transmitting energy through electromagnetic fields (Lu et al., 2016). In general, WPT consists of a transmitter device connected to a source of power, which converts the power to the time-varying electromagnetic field and a receiver that receive the power and converts it back to dc...
or ac electric current and used for charging the mobile device (Lu et al., 2016). The WPT promises to eliminate the use of wires and batteries, thus increasing the mobility, convenience and safety of mobile devices (Ibrahim et al., 2016). Moreover, using this technique, power is wirelessly transferred even where interconnecting wires are inconvenient, hazardous, or not possible.

There are mainly two techniques of power transfer, namely near field and far-field. In the first category, power is transferred over short distances by magnetic fields using inductive and capacitive coupling (Erfani et al., 2017, 2018a, b). Inductive coupling is the most widely used for applications like charging of mobile phones, induction cooking and wirelessly charging of implantable medical devices like artificial cardiac pacemaker (Basnayaka et al., 2020). However, in far-field technique, also called power beaming, power is transferred by electromagnetic radiation beams, like microwaves (García et al., 2019), which could transport power over long distance and delivered to the receiver. Their applications include solar power satellites and wireless powered drone aircrafts (Bush, 2014).

As shown in Figure 1, power is wirelessly transferred to a user terminal in indoor scenario from a distantly placed far-field charging unit (FFCU) consisting of an array antenna to focus the electromagnetic radiation toward the terminal. Rectennas within the terminal rectify the received signal. WPT enables the charging of devices more conveniently as well as easy to use. Of course, there is no hassle involved in cabling and plugging. Although WPT is not a new concept (Sheik Mohammed et al., 2014), its history goes back to 1830, when the concept introduced by Faraday’s was first used inductive coupling to transfer power wirelessly. The various technologies developed thereafter for wireless transfer of power are summarized in Table 1.

As most of the papers are based on inductive coupling that allows power transfer through near field radiations, only few papers claim for far-field WPT (Dunbar et al., 2015; Jadidian and Katabi, 2014). Generally, antennas designed for WPT are based on fixed substrate (Heo et al., 2017).

Recently few papers claimed to design conformal antenna (Hashemi et al., 2019; Peng et al., 2020; Pham et al., 2011; Subbaraman et al., 2013) but they are not used for power transfer. Very few efforts are found in literature where flexible substrates were used for power transfer (Bakytbekov et al., 2018; Bao et al., 2019; Haerinia and Noghanian 2019;
Heo et al., 2017; Palazzi et al., 2018). To the author’s best knowledge this is first time an array antenna is investigated on flexible Kapton polyimide substrate as a transmitting antenna as oppose to receiving rectennas used in RF harvesting systems. Kapton polyimide is both conformable and light weight. Proposed array antenna has broadside gain and beam width value of 16.38 dB and 29.4°, respectively. The measured results for the proposed antenna are not included due to the restriction imposed by the COVID-19 pandemic. This paper is organized as follows: Section 2 provides details about substrate selection and the antenna design. The results are discussed in section 3, and finally, conclusions are drawn in section 4.

2. Antenna design
2.1 Choice of substrate
The antenna substrate choice depends on dielectric properties, susceptibility to miniaturization, resistance to mechanical deformations, i.e. bending, wrapping and twisting and endurance in the external environment (Kirtania et al., 2020). In general, 3 types of substrate are used for flexible antenna design.

1. Thin glass
2. Metal foils
3. Plastic/polymer

Later one is generally used because glass is brittle, and metallic foils are costly, and surface roughness is more environmental (Kirtania et al., 2020). Flexible substrates nowadays are preferred over fixed substrates because they are cheap, light weight and durable (Wong and Salleo, 2009).

As observed from Table 2, it can be seen that Kapton has very good chemical and mechanical properties among other commonly used flexible substrate like PET (polyethylene terephthalate), PEN (polyethylene naphthalene) and LCP (liquid crystalline polymers).

| Technology                  | Devices                          | Range                               | Frequency          |
|-----------------------------|----------------------------------|-------------------------------------|--------------------|
| Inductive coupling          | Wire coils                       | Millimeters to centimeters          | Below 100 kHz      |
| Magnetic resonant coupling  | Tuned wire coils, lumped element | A few meters, typically 4 to 10 times the coil diameter | Hundreds of MHz—GHz |
| EM radiation                | Dish antenna, antenna array, rectenna | Several meters to hundreds of kilometers | 800 MHz to 94 GHz (Valenta and Durgin, 2014) |
| Laser power beaming        | Laser emitter, photovoltaic receiver | Up to kilometers                   | THz                |

Table 1. Technologies for wireless power transfer

| Material                   | PET | PEN | Kapton | LCP | Paper |
|---------------------------|-----|-----|--------|-----|-------|
| Mechanical properties     | Good| Good| Excellent| Good| –     |
| Heat resistance           | Low | Very good | Excellent | Good| –     |
| Chemical resistance       | Good| Good| Good | Excellent | –     |
| Electrical properties     | Good| Good| Good | Good | Good  |

Table 2. Properties of different flexible substrates (Wong and Salleo, 2009)
Moreover, Kapton has minimum tangent loss value among PET and PEN (Kirtania et al., 2020). Both PET and PEN provide excellent conformability but these substrates cannot resist high temperature (Kirtania et al., 2020). Therefore, Kapton is chosen as substrate for antenna design having substrate thickness \( h = 0.127 \text{ mm} \) and dielectric constant \( \varepsilon_{\text{sub}} = 3.2 \) and tan \( \delta = 0.012 \) (Yang et al., 2016).

2.2 Microstrip patch antenna

Microstrip antenna, in its most basic form, comprises of two thin metallic layers separated by a dielectric. Top metallic layer having specific shape behaves as radiating patch and the bottom metallic layer act as a ground plane and a dielectric substrate sandwiched between the two plates. Generally, copper and gold are used as metallic radiating layer due to their high conductivity. The patch can be of any shape but simple shapes are preferred because basic shapes are easy to analyze by the available theoretical models. Square, rectangular, dipole, triangular, elliptical and circular are some basic shapes that are used for patch antenna. However, in this paper a rectangular patch is used instead of circular patch because it has demonstrated higher gain (Balanis, 2005). Different types of feeding techniques are available for patch antennas. In general, a patch antenna, which is fed either by coaxial line or strip line. The current and voltage in the patch is 90° out of phase.

Using the transmission line model, and operating frequency \( f_0 \), height \( h \) and dielectric constant of the substrate \( \varepsilon_{\text{sub}} \), the size of the patch and ground planes are determined (Balanis, 2005). The microstrip patch antenna is used as it is one that offers light weight and is low profile (Gangwar and Alam, 2016). It is a wide beam narrowband antenna which can be manufactured easily by the printed circuit technology. The size of microstrip antenna is usually related to its operating wavelength that is \( \lambda/2 \) (Balanis, 2005). The design of proposed microstrip antenna with all its parameters is shown in Figure 2.

Although, the ground plane is assumed to be infinite in transmission line model, in all practical scenario, finite size plane is used. By substituting \( f_0, h, \varepsilon_{\text{sub}} \) and \( c \), the dimensions of

![Figure 2. Proposed unit microstrip patch antenna on Kapton substrate](image_url)
Length and width of the patch antenna calculated to be 5.1 and 6.47 mm respectively.

The inset length of the patch \( y_0 \) as shown in Figure 2 is calculated such that the input impedance of the patch is equal to the characteristic impedance of the feed line which is 50\( \Omega \).

\[
R_{\text{Input}}(y = y_0) = R_{\text{Input}}(y = 0) \left( \frac{\pi}{L y_0} \right)
\]  

(1)

Where, \( R_{\text{Input}}(y = 0) \) is the input impedance at the leading radiating edge of the patch and \( R_{\text{Input}}(y = y_0) \) is the characteristic input impedance (50\( \Omega \)). The antenna is fed using an inset microstrip feed having dimensions 2.9 \( \times \) 0.305 mm. The ground plane is defined by perfect electric conductor boundaries. An air box must be specified as open space in the model, so that radiation from the design is absorbed and not re-reflected. The air box needs to be quarter-wavelength long (Balanis, 2005). The length, width and height of air box in the design is 42.75 mm \( \times \) 42.75 mm \( \times \) 18.87 mm respectively.

2.3 Antenna array
An antenna array consists of \( N \) spatially separated radiating elements. Each element has its own induction field. The elements are placed such that each one lies in the neighboring one’s induction field. Therefore, the overall radiation pattern produced by them would be the vector sum of the individual elements (Balanis, 2005). Array antenna is used to enhance performance like increasing directivity and gain.

Single elements are used to design antenna array with proper inter-element spacing, generally \( \frac{\lambda}{2} \) along both \( x \) and \( y \) axis. Array antennas can transfer power at much larger distance compared to single element. Figure 3 shows 4 \( \times \) 4 proposed square array with inter-element spacing (\( d \)) of 9.375 mm, increasing the value of \( d \) will cause grating lobes to occur and decreasing value of \( d \) will increase coupling between patches thereby decreasing performance in both the cases. Therefore, inter-element spacing between the antenna elements and number of elements used in arrays should be kept in mind while designing these antennas. Total area occupied by designed system is 75 \( \times \) 75 mm.
3. Simulation results and discussion

The initial simulations of unit microstrip antenna are performed from the dimensions obtained from design equations (Balanis, 2005) and mentioned in Table 3. Further optimization of the dimensions is performed to achieve good resonance. Ansys® Electronics desktop, HFSS (high frequency structure simulator) is used to simulate both the unit patch and array antenna performances (Ansys, 2021).

3.1 Unit patch antenna

The return loss ($S_{11}$) plot for the unit patch antenna is shown in Figure 4. The value of $S_{11}$ is equal to $-45.07$ dB at the resonance frequency. The $-10$ dB bandwidth of the antenna is 226.2 MHz. Similarly, Figure 5 presents the antenna gain having maximum value of 4.8 dB. Antenna gain is one of the important parameters to determine antenna performance, which is defined in Eq. (2) as product of antenna efficiency and directionality.

$$G = e \times D$$  \hspace{1cm} (2)

Figure 6 shows the far-field radiation pattern of the unit patch antenna with maximum radiation in broadside direction $\theta = 0^\circ$ direction and minimum radiation in direction of $\theta = 90^\circ$.

3.2 Antenna array

Using the unit patch antenna, an antenna array is modeled and simulated. Figure 7 shows return loss ($S_{11}$) of the antenna array. A frequency shift of 20 MHz is noticed due to coupling between elements as shown in Figure 8. Mutual coupling between array elements is

| Parameters         | Analytic dimensions | Optimized dimensions |
|--------------------|---------------------|----------------------|
| Length of the patch ($L$) | 5.10 mm             | 5.151 mm             |
| Width of the patch ($W$)  | 6.47 mm             | 6.7 mm               |

Table 3. Analytic and optimized antenna parameters

Figure 4. Return loss ($S_{11}$) for proposed unit patch antenna
considerably less than \(-35\) dB (see Figure 8). Minimum value of \(S_{11}\) is \(-29.16\) of 2nd port and maximum value of \(S_{11}\) is equal to \(-41.52\) of 1st port. Impedance bandwidth of 240 MHz is achieved. Similarly, Figure 9 shows gain plot of the designed antenna array, which depicts value of gain at \(\phi = 0^\circ\) (\(x-z\) plane) and at \(\phi = 90^\circ\) (\(y-z\) plane). The maximum value of gain

**Figure 5.** Gain plot for proposed patch antenna

**Figure 6.** Far-field radiation pattern for proposed patch antenna
obtained at $\theta = 0^\circ$ is 16.38 dB with 3 dB beam width of 29.4°. Figure 10 shows the variation of radiation efficiency with frequency, which is 36.67% at resonance frequency and decreases as frequency is increased. Figure 11 presents radiation pattern of array antenna. The main beam is narrower and focused than the single element which is desired for power transfer, side and back lobes have less power than main lobe. Figure 12 presents co- and cross-polarization field components of antenna. Cross-polarization level is well below $-34.23$ dB. Figure 13 provides antenna scanning range of $-15^\circ$ to $+15^\circ$ in both the elevation and azimuth planes with gain value more than 14 dB. Due to dielectric losses of flexible Kapton substrate, its radiation efficiency is low at 36.67%. Table 4 summarized both unit patch and array antenna result outcomes. Both bandwidth and gain increases in array. Increment in gain is obvious because more elements are used but bandwidth also slightly increases due to resonance coupling between array elements.
4. Conclusion and future scope

In this work, a $4 \times 4$ microstrip antenna array using flexible Kapton polyimide substrate is proposed to operate at 16 GHz for WPT application. It exhibits high simulated broadside gain of 16.38 dB along with $-10$ dB bandwidth of approximately 240 MHz. Also, it offers a wide beam width of $29.4^\circ$ with very low cross-polarization levels of $-34.23$ dB. The antenna array beam can scan from $-15^\circ$ to $+15^\circ$ in both the elevation and azimuth planes. The proposed antenna array is capable of focusing the electromagnetic energy toward a targeted user terminal with an efficiency of 36.67%. The designed antenna uses flexible Kapton polyimide substrate which provides conformability to the designed antenna. Thus, promising results make this antenna array a good probable candidate for future wireless charging applications. In future we are going to perform bending of the array structure and how it will affect different characteristics of antenna. Bending of designed array antenna on a PVC plastic cylinder is shown in Figure 14.
Figure 11. Far-field radiation pattern for proposed antenna array.

Figure 12. Co and cross-polarization fields of antenna array.
Antenna array
design on
flexible
substrate

Figure 13.
Beam scanning range
of array antenna in
Elevation plane (−15
deg to +15 deg)

Table 4.
Antenna array
parameter obtained
after simulation

| Parameters           | Unit Antenna | Antenna array |
|----------------------|--------------|---------------|
| Bandwidth            | 226.2 MHz    | 240 MHz       |
| Peak gain            | 3.02 dB      | 16.38 dB      |
| Radiation efficiency | 46.187%      | 36.67%        |
| Beam width           | 55.7°        | 29.4°         |

Figure 14.
Study of bending
structures

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