Antenna array design on flexible substrate for wireless power transfer

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Received 29 March 2021
Revised 12 April 2021
Accepted 13 April 2021

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 a time-varying electromagnetic field and a receiver that receive the power and converts it back to dc

Authors acknowledge Prof. Syed Azeemuddin, Centre of VLSI and EMBEDDED SYSTEM, IIIT, Hyderabad for his motivation and guidance.

Frontiers in Engineering and Built Environment
Vol. 1 No. 1, 2021
pp. 55-67
Emerald Publishing Limited
e-ISSN: 2634-2502
p-ISSN: 2634-2499
DOI 10.1108/FEBE-03-2021-0018

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.

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;

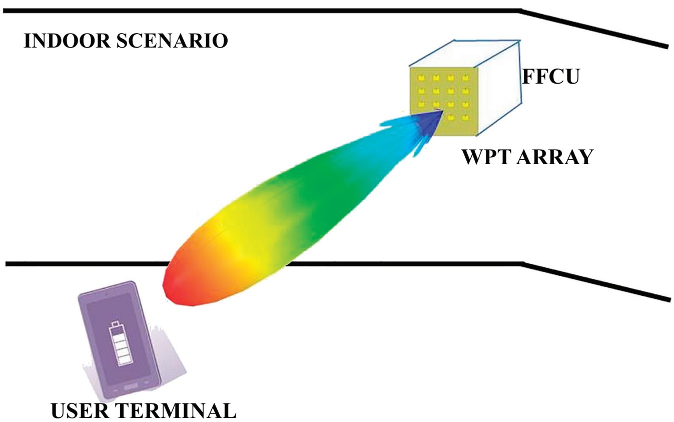

Figure 1.
Antenna array for FFCU to wirelessly transfer power in indoor scenario

Technology	Devices	Range	Frequency
Inductive coupling	Wire coils	Millimeters to centimeters (Choudhary *et al.*, 2011)	Below 100 kHz
Magnetic resonant coupling	Tuned wire coils, lumped element resonators	A few meters, typically 4 to 10 times the coil diameter (Rayes *et al.*, 2016)	Hundreds of MHz–GHz (Jadidian and Katabi, 2014)
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

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).

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 mm and dielectric constant (ε_{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 90º out of phase.

Using the transmission line model, and operating frequency (f_0), height (h) and dielectric constant of the substrate ε_{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 $\frac{\lambda}{2}$ (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_o, h, ε_{sub} and c, the dimensions of

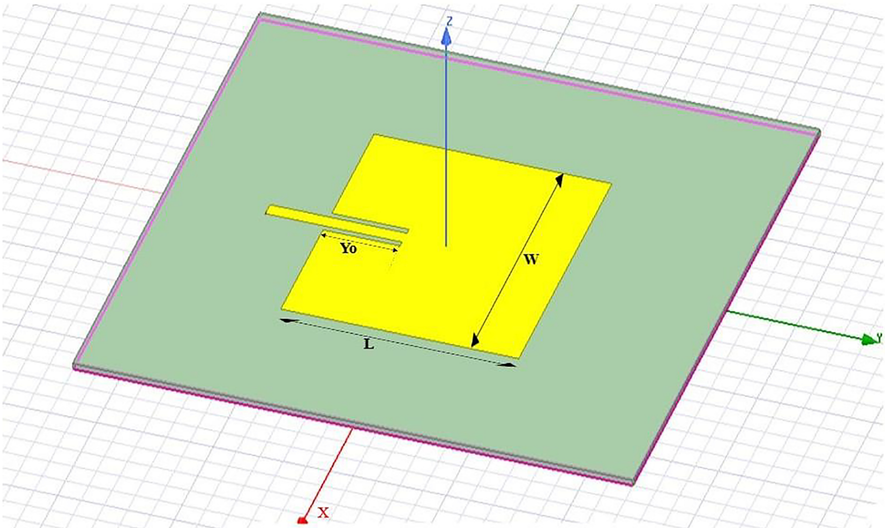

Figure 2.
Proposed unit microstrip patch antenna on Kapton substrate

patch are calculated. 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 50Ω.

$$R_{\text{Input}}(y = y_0) = R_{\text{Input}}(y = 0)\left(\frac{\pi}{L}y_0\right) \quad (1)$$

Where, R_{Input} $(y = 0)$ is the input impedance at the leading radiating edge of the patch and R_{Input} $(y = y_0)$ is the characteristic input impedance (50 Ω). The antenna is fed using an inset microstrip feed having dimensions 2.9 × 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 × 42.75 mm × 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 × 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 × 75 mm.

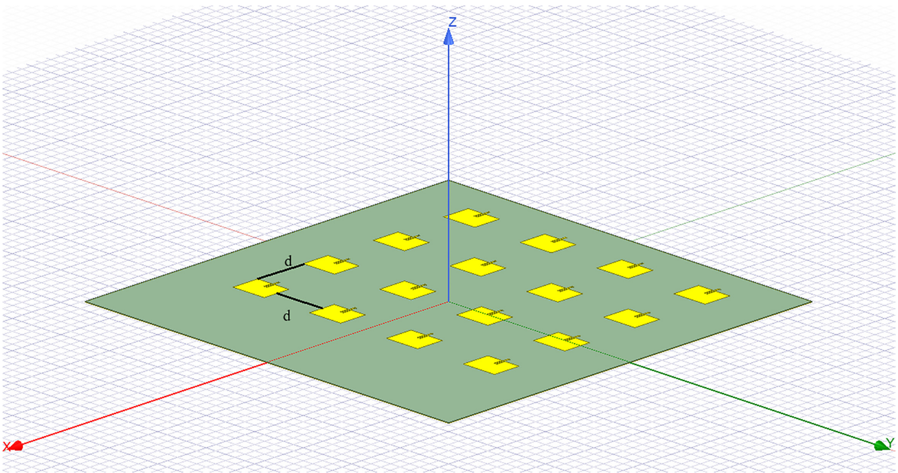

Figure 3.
Proposed 4 × 4 Microstrip antenna array on Kapton substrate

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.

$$G = e \times D \tag{2}$$

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

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

Table 3.
Analytic and optimized antenna parameters

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

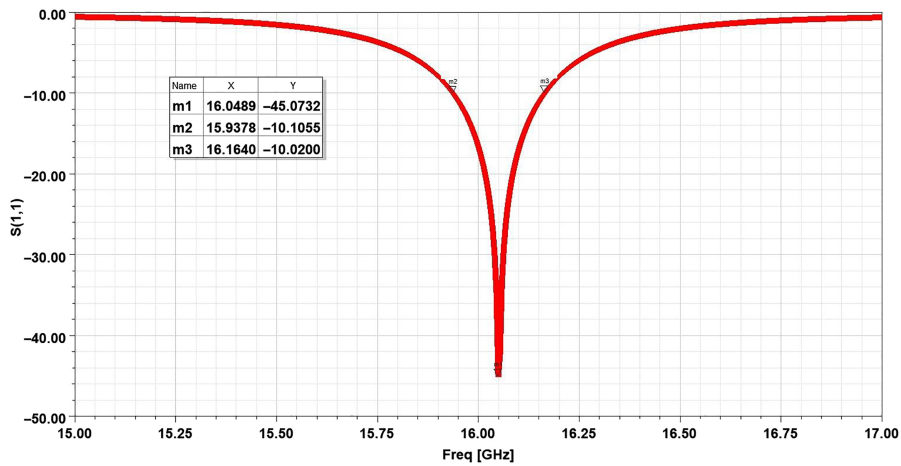

Figure 4.
Return loss (S_{11}) for proposed unit patch antenna

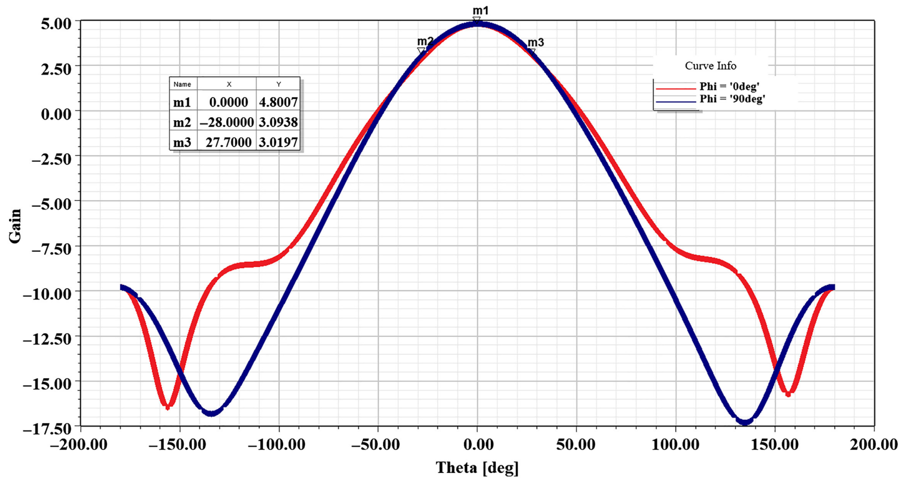

Figure 5.
Gain plot for proposed patch antenna

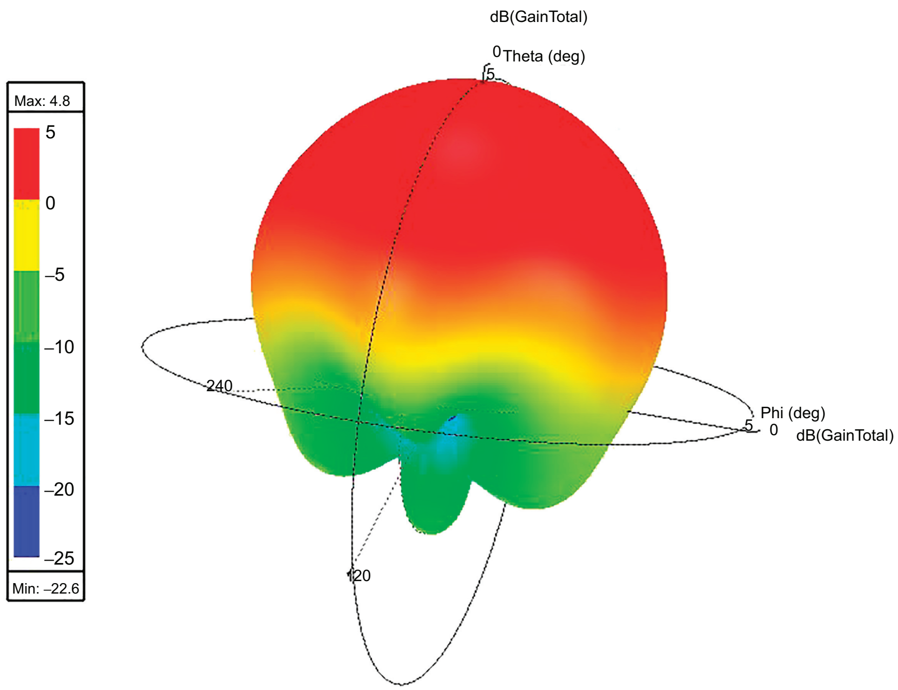

Figure 6.
Far-field radiation pattern for proposed patch antenna

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° (*x*–*z* plane) and at phi = 90° (*y*–*z* plane). The maximum value of gain

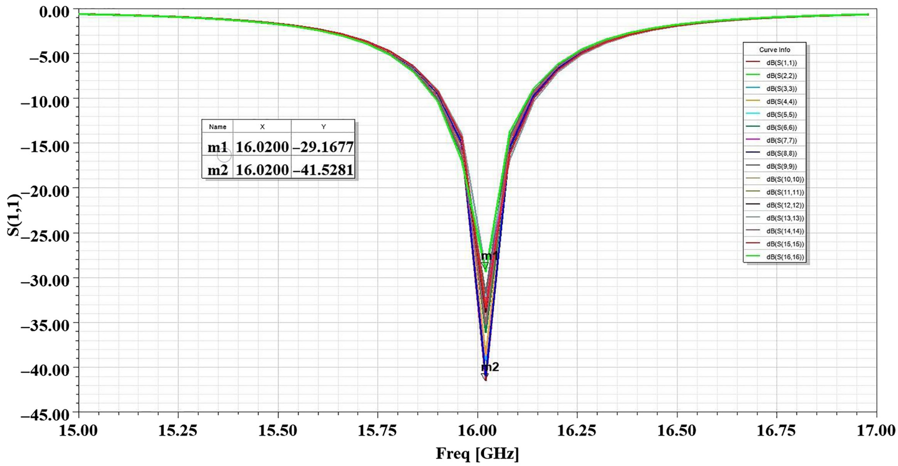

Figure 7.
Return loss (S_{11}) for proposed antenna arrays

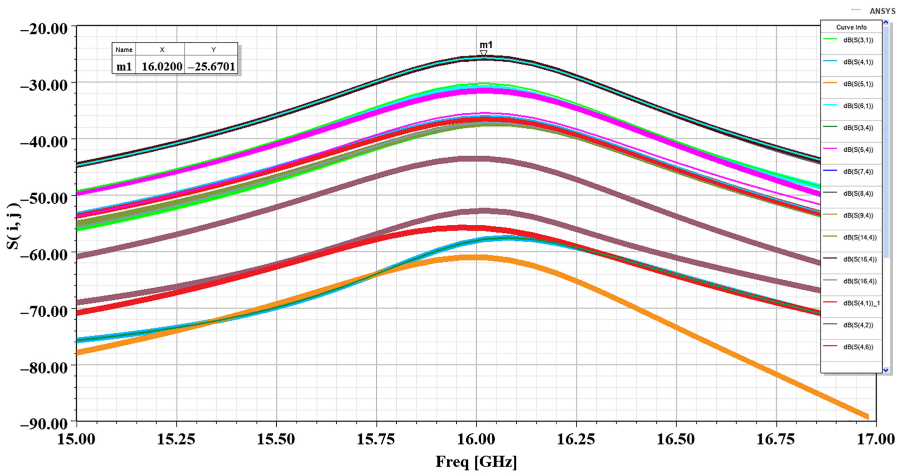

Figure 8.
Mutual coupling (S_{ij}) between antenna array elements

obtained at $\theta = 0°$ 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° to +15° 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.

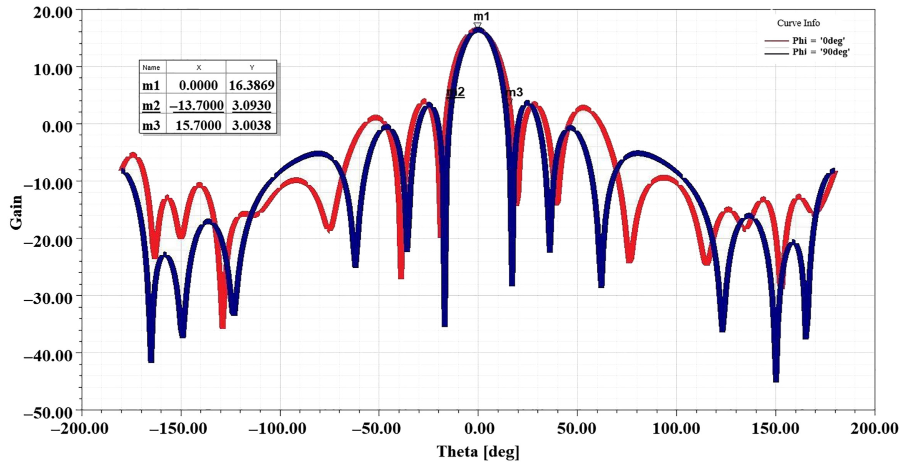

Figure 9.
Gain plot for proposed antenna array

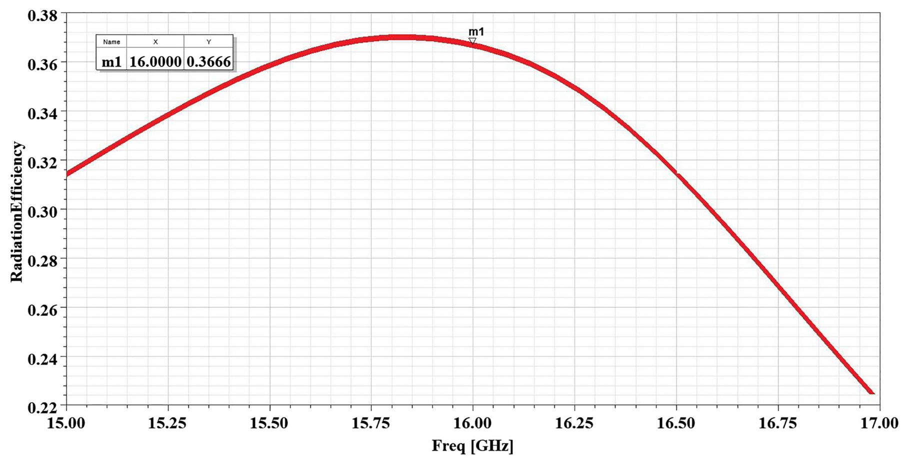

Figure 10.
Radiation efficiency versus frequency

4. Conclusion and future scope

In this work, a 4 × 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° with very low cross-polarization levels of −34.23 dB. The antenna array beam can scan from −15° to +15° 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.

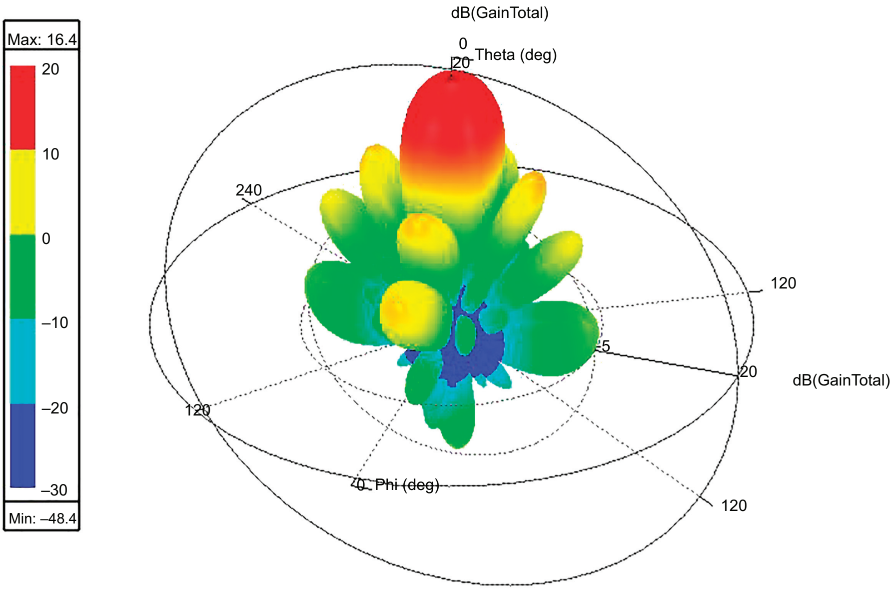

Figure 11.
Far-field radiation pattern for proposed antenna array

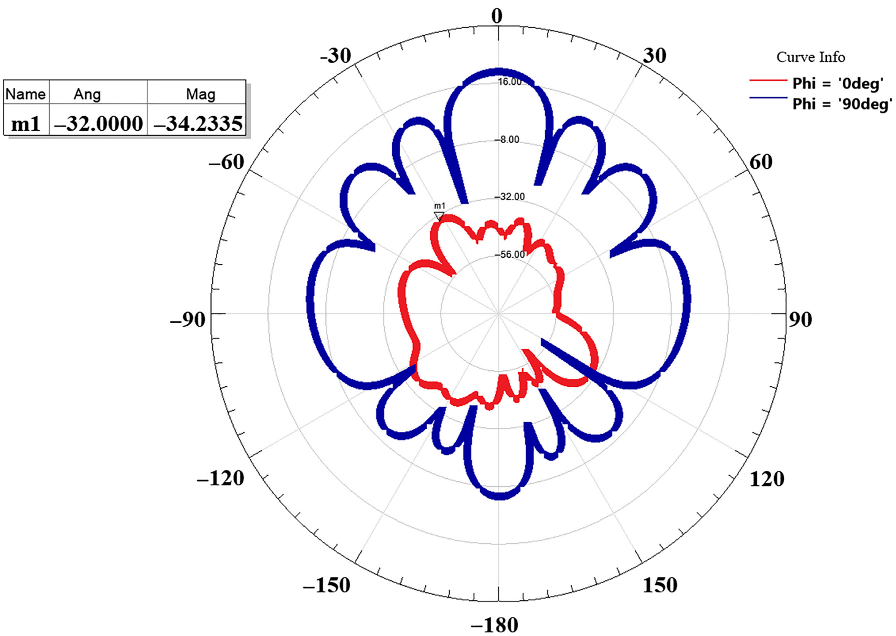

Figure 12.
Co and cross-polarization fields of antenna array

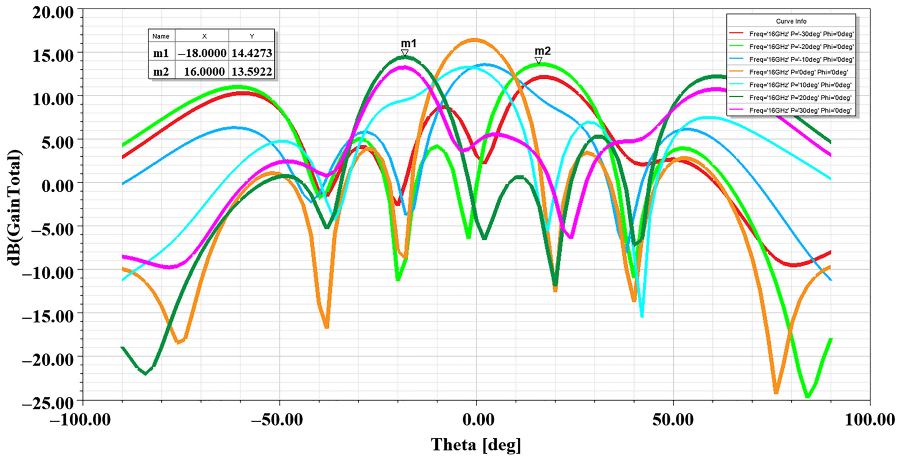

Figure 13. Beam scanning range of array antenna in Elevation plane (–15 deg to +15 deg)

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°

Table 4. Antenna array parameter obtained after simulation

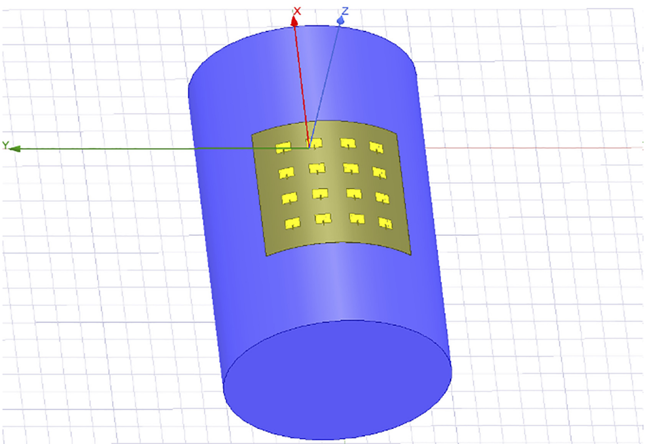

Figure 14. Study of bending structures

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