

# Assessment of Kapton-based Flexible Antenna for Near Field Wireless Energy Transfer

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**Abstract** — This letter presents the design of a flexible highly efficient antenna for Wireless Energy Transfer (WET) at 13.56 MHz. The proposed antenna uses very thin kapton, with a thickness of 25  $\mu\text{m}$  as a substrate, and an 18  $\mu\text{m}$  layer of copper as the conductive material. The 40 mm x 40 mm 6 loop antenna produces almost 90% ETE (energy transfer efficiency) and a bandwidth (BW) of almost 4 MHz for inductive wireless communications. This flexible antenna is suitable for use in small mobile devices, for wireless charging and communication purposes at the NFC operating frequency. In addition, kapton offers very high durability, high mechanical strength, and unique distortional resistance to harsh environments and corrosive aqueous etchants, in this way increasing the reliability of the antenna.

**Index Terms** — Flexible antenna, high efficiency, kapton, Near Field Communication (NFC), Wireless Energy Transfer (WET).

## I. INTRODUCTION

Near Field Communication (NFC) enables data transfer between devices. Since it is facilitated through inductive coupling, NFC can also be used to enable the transfer of energy between these devices. Due to NFC's unique ability, many high- and mid-end smartphones come with embedded NFC features. However, with the current technology, NFC antennas embedded in smartphones are only used for data transfer, rather than wireless charging.

Various substrate materials have been investigated for use in energy transfer applications. Some studies

have achieved insensitivity to distance and strong magnetic coupling using low-cost glass reinforced epoxy laminated boards (FR 4) [1-3]. A Nickel-Zinc-based ferrite substrate has also been used to implement near-field antennas with high efficiency at 13.56 MHz [8]. However, the growing demand for flexible electronic devices necessitates further research into the implementation of antennas on flexible substrates. Some of the more popular flexible substrates found in literature include kapton polyimide film, polydimethylsiloxane (PDMS) and polyethylene (PET). Yu has proposed a multi-layer spiral antenna for wireless power transfer at 300 kHz using copper coils separated by kapton films [4]. The author manages to transfer 5 Watts of power over a distance of two times the coil diameter. Choo has designed a flexible antenna for near-field communication at the UHF frequency of 912 MHz [5]. The author used printed copper strip line on flexible polyethylene (PET) to couple a reader and a microchip, solely for wireless communication [5]. However, except for a few examples of the application of flexible PDMS substrates in telemetry systems [6], not much research has been carried out on flexible antenna substrates for wireless energy transfer.

To the best of our knowledge, there are no papers on the study and design of flexible antennas for simultaneous wireless communication and energy transfer at 13.56 MHz. Therefore, this research proposes a design of a flexible antenna for wireless energy transfer, which supports wireless data transfer as well. A frequency of 13.56 MHz is chosen to fit the standard operation frequency of NFC. Kapton is assessed as the substrate because of its

flexibility, the possibility to use very thin layers (in contrast to PDMS), the rather low cost (in comparison with graphene), and the very high durability and mechanical strength.

## II. ANTENNA GEOMETRY

In order to fit into a smartphone, the antenna is sized at 40 mm x 40 mm. The antenna topology is shown in Fig. 1 and its dimensions are given in Table 1. For a perfect circular loop, the best operation distance with the strongest magnetic field flux is  $r = d\sqrt{2}$  [7], where  $d$  is the operating distance and  $r$  is the antenna's radius. Assuming that changing the shape to a square will not change this characteristic drastically, the operating distance for the wireless energy transfer link is set at 14.14 mm.

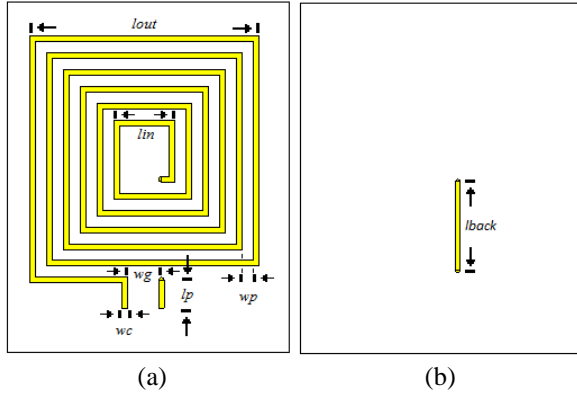


Fig. 1. Antenna topology: (a) front view and (b) back view, connected by vias.

Table 1: Antenna dimensions

Parameter	Value
Outer loop length, $l_{out}$	41 mm
Inner loop length, $l_{in}$	4 mm
Strip width, $w_c$	1 mm
Gap width, $w_g$	2 mm

The transfer efficiency of a pair of antennas in an energy transfer link is calculated by [8]:

$$\eta = \frac{k^2 Q_1 Q_2}{(1 + \sqrt{1 + k^2 Q_1 Q_2})^2}, \quad (1)$$

where  $Q_1$  and  $Q_2$  are the quality factors of the transmitting and receiving antenna respectively:

$$Q_1 = \frac{\omega L_1}{R_1}, \quad (2)$$

$$Q_2 = \frac{\omega L_2}{R_2}, \quad (3)$$

$$\omega = 2\pi f, \quad (4)$$

$k$  is the coupling coefficient between both antennas and can be determined using:

$$k = \frac{M}{\sqrt{L_1 L_2}}. \quad (5)$$

Since the kapton layer is extremely thin, the inductance of each antenna can be computed as [9]:

$$L_{1,2} = 0.635\mu l_{avg} \left[ \ln\left(\frac{2.07}{l_p}\right) + 0.18l_p + 0.13l_p^2 \right], \quad (6)$$

where  $\mu$  is the permeability of the background medium and,

$$l_p = \frac{l_{out} - l_{in}}{l_{out} + l_{in}}, \quad (7)$$

$$l_{avg} = \frac{l_{out} + l_{in}}{2}. \quad (8)$$

The mutual inductance between both antennas,  $M$  can be obtained using [10]:

$$M = \left(\frac{4}{\pi}\right)^2 2 \sum_{i=1}^{i=N} M_i \quad \text{and}$$

$$M_i = \frac{\mu_o \pi a_i^4}{2(2a_i^4 + d^2)^{\frac{3}{2}}} \left( 1 + \frac{15}{32}\gamma^2 + \frac{315}{1024}\gamma^4 \right), \quad (9)$$

$$\gamma = \frac{2a_i^2}{2a_i^2 + d^2}, \quad (10)$$

where  $N$  is the number of turns and  $a_i = l_{out} - (N - 1)(w_c + w_g) - w_c/2$ . The skin depth,  $\delta$  and the resistance of each antenna are determined by using:

$$R_{DC} = \frac{\rho l}{A}, \quad \delta = \frac{\sqrt{\rho}}{\sqrt{\pi f \mu_o}}, \quad (11)$$

$$R = \frac{R_{DC}}{4\delta} \left( \frac{t_c}{1 - e^{-\frac{t_c}{\delta}}} \right), \quad (12)$$

where  $\rho$  is the resistivity of copper ( $1.7 \times 10^{-8}$  Wm),  $A$  is the cross-sectional area of the strip, and  $t_c$  is the thickness of the copper conductor.

With reference to Fig. 1,  $l$  and  $A$  can be defined as:

$$l = 6(w_p + w_c) + l_{back} + \frac{l_{out} + w_p - w_g}{2} + l_{out} + w_p + 2(l_{out} - w_c) + 2 \sum_{i=1}^{i=2N-1} (l_{out} - (i - 1)w_p - iw_c), \quad (13)$$

$$A = w_c t_c. \quad (14)$$

The bandwidth of the antenna is defined as the frequency interval in between the two -3 dB points with respect to the value at the resonant frequency.

## III. RESULTS AND DISCUSSION

Using described model in previous section, transfer efficiency of the antennas is calculated using Matlab. Based on the mathematical model, transfer efficiency obtained is 81.28%. However, this computation does not take the dielectric effects into consideration. Hence, full-wave simulations are employed to examine the transfer efficiencies obtained using different dielectric substrates.

There are various kapton substrates in the market, as given in Table 2. Since the kapton itself is extremely thin, it will have a negligible effect on the energy transfer

link. The copper thickness does have an effect on the efficiency of this transfer link, but it will be shown that a thickness of 18  $\mu\text{m}$  already yields efficiencies near

90%. The energy transfer system uses identical antennas for transmitter and receiver at an operating distance of 14.14 mm, as shown in Fig. 2.

Table 2: Kapton with different thicknesses of substrate and copper, as available from Shengyi Technology Co, Ltd

Substrate	Dielectric Constant ( $\mu$ )	Loss Tangent	Substrate Thickness	Copper Thickness
Kapton	3.6	0.031	12.5 $\mu\text{m}$	18 $\mu\text{m}$
Kapton	3.5	0.030	25 $\mu\text{m}$	18 $\mu\text{m}$
Kapton	3.5	0.030	25 $\mu\text{m}$	35 $\mu\text{m}$
Kapton	3.5	0.030	75 $\mu\text{m}$	35 $\mu\text{m}$

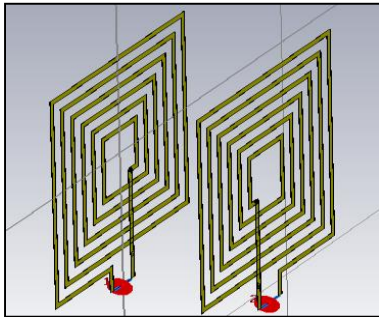


Fig. 2. Energy transfer topology.

Both antennas have been matched using the lumped element technique, see Fig. 3. Based on a compromise between efficiency, flexibility, and mechanical strength, the kapton is chosen 25  $\mu\text{m}$  thick and the copper is chosen 18  $\mu\text{m}$  thick. The resulting efficiency is given in Fig. 4. All simulations were done with CST Microwave Studio.

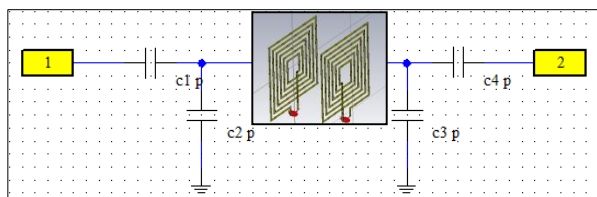


Fig. 3. Wireless link with matching networks for both antennas.

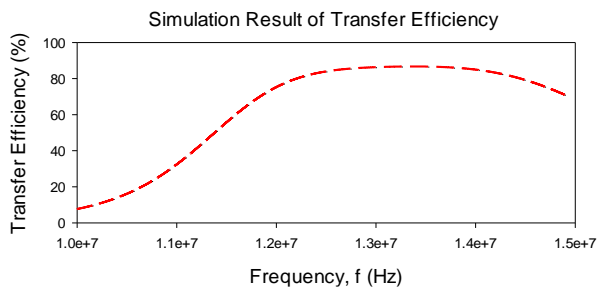


Fig. 4. Efficiency of the antenna using 25  $\mu\text{m}$  kapton and 18  $\mu\text{m}$  copper thickness.

The antenna was fabricated and measured, see Fig. 5. S-parameters were recorded and analyzed, and both antennas were impedance matched using lumped elements. The capacitor values available in the market nearest to the optimal values were selected, see Table 3.

It is easily shown that the efficiency of the energy transfer link  $P_{\text{received}}/P_{\text{transmitted}}$  is given by  $|S_{21}|^2$ . This parameter is shown in Fig. 6.

Table 3: Capacitor values used in the impedance matching

	$C_1$ (pF)	$C_2$ (pF)	$C_3$ (pF)	$C_4$ (pF)
Simulation	100	60	62	100
Actual	98.61	58.89	61.23	95.71

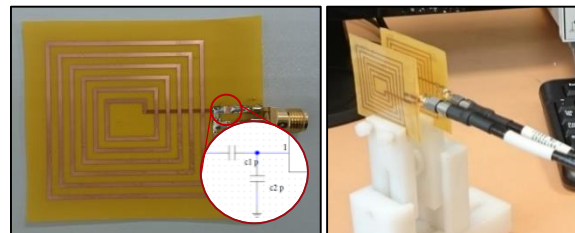


Fig. 5. Fabricated antenna and measurement setup.

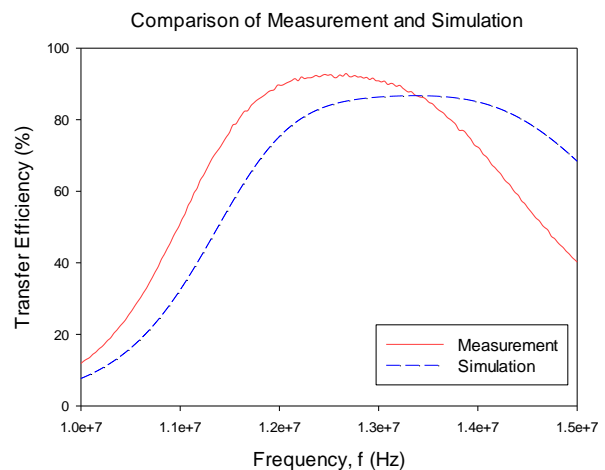


Fig. 6. Realized transfer efficiency.

At a distance of 14.14 mm, the energy transfer

efficiency achieved is as high as 86.61% and 83.82% in simulations and measurements, respectively. The difference of 2.79% with the simulated value is caused by the tolerances on the etching process, and slightly deviating distance from the simulated distance in real life.

Based on this result, it can be clearly concluded that kapton is a suitable material to be used for wireless energy transfer. Kapton can offer transfer efficiencies as high as rigid materials like FR4, with the huge advantage of adding flexibility.

Figure 7 shows that the optimal frequency of the transfer system decreases slightly when the operating distance is increased. This happens because changing the distance will alter the mutual inductance between transmitter and receiver antenna. Hence, both antennas will not be perfectly matched anymore. Therefore, at the NFC frequency, the efficiency of the wireless energy transfer is significantly changed, see Fig. 8.

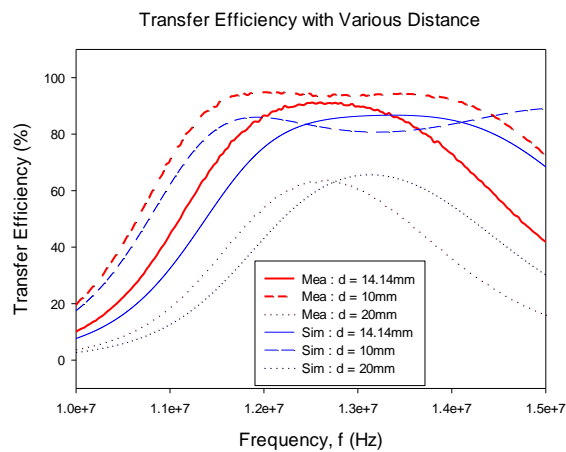


Fig. 7. Transfer efficiency as a function of frequency, simulation (Sim) and measurement (Mea) for several distances,  $d$ .

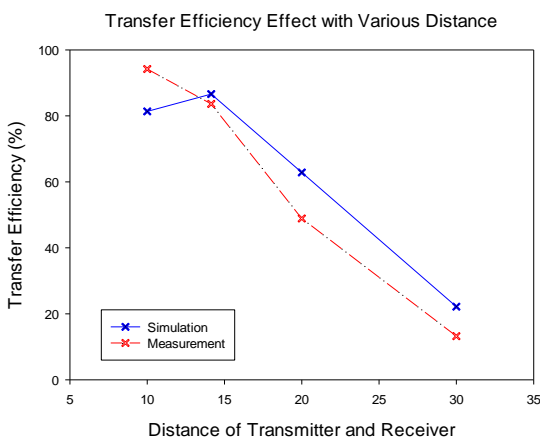


Fig. 8. Change in measurement of transfer efficiency with varying distance between antennas.

When the distance between both antennas is smaller than the optimum distance, a multi-resonance appears, as shown in Fig. 7. Multi-resonance condition will result two maximum transfer efficiencies at two different frequencies. This phenomenon is caused by an over-coupling condition, which occurs when the transmitter is too close to the receiver and creates frequency splitting phenomenon. As a result, the transfer efficiency at operating frequency will reduce significantly. The discrepancy in the trend of the change of transfer efficiency with distance between antennas for measurement and simulation is recorded. The different is contributed by the non-exist exact capacitor value for matching circuit in market. The 5% capacitors tolerance also causes the difference between measurement result and simulation result

Since we are considering a flexible substrate, bending may be an issue, since it may occur, accidentally or on purpose, in practical situations. The bending situation studied is given in Fig. 9. One of the two antennas is bent with a radius of 20 mm. Results for bending are given in Fig. 10. It is shown that bending the antenna will slightly reduce its efficiency. However, the drop of 4.5% in efficiency (from 83.6%) is acceptable.

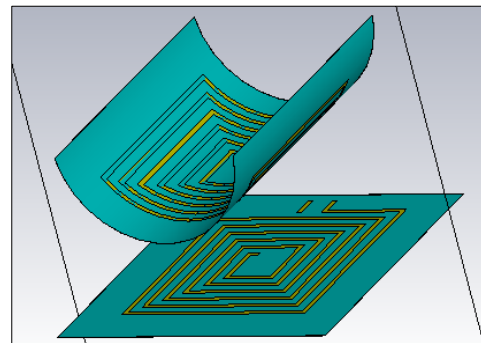


Fig. 9. Bending situation with bending radius  $r = 20$  mm.

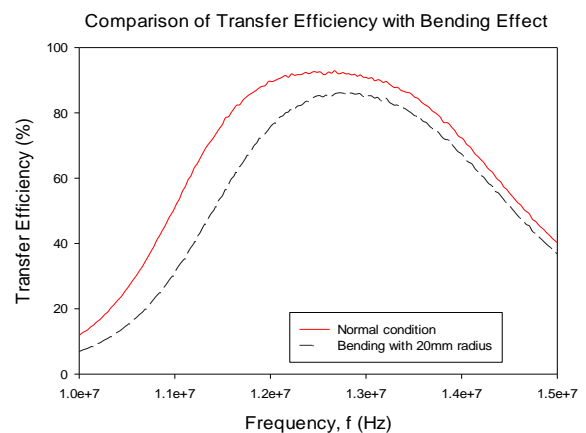


Fig. 10. Measurement for effect of bending on transfer efficiency.

Figure 11 shows that the antenna has a large bandwidth of 3.86 MHz around the operating frequency of 13.56 MHz at matching distance, 14.14 mm. This is sufficient for inductive signal transmission. This proves that antennas using kapton substrates are suitable for wireless communications as well.

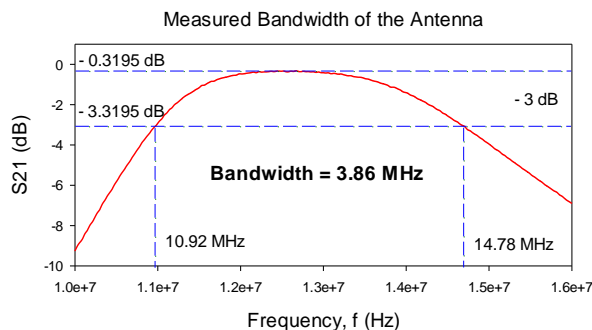


Fig. 11. Measured bandwidth of the antenna.

#### IV. CONCLUSION

It is shown that kapton is suitable to be used as an antenna substrate for WET purposes. Results show that this flexible material can produce high performance in terms of ETE and bandwidths, comparable to rigid substrates such as FR4. In addition, kapton is flexible, and that can increase the robustness of the antenna by enabling it to fit with any device shape.

#### ACKNOWLEDGMENT

This research was supported by the Ministry of Higher Education, Universiti Teknikal Malaysia Melaka and Universiti Teknologi Malaysia.

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