Flexible Patch Rectennas for Wireless Actuation of Cellulose Electro-active Paper Actuator

Sang Yeol Yang*, Jaehwan Kim† and Kyo D. Song**

Abstract – This paper reports a flexible patch rectenna for wireless actuation of cellulose electro-active paper actuator (EAPap). The patch rectenna consists of rectifying circuit layer and ground layer, which converts microwave to dc power so as to wirelessly supply the power to the actuator. Patch rectennas are designed with different slot length at the ground layer. The fabricated devices are characterized depending on different substrates and polarization angles. The EAPap integrated with the patch rectenna is actuated by the microwave power. Detailed fabrication, characterization and demonstration of the integrated rectenna-EAPap actuator are explained.

Keywords: Microwave power transmission, Patch rectenna, Flexible substrate, Wireless actuation, Electro-active paper

1. Introduction

Wireless power transmission is a promising technique for the long-term power supply of wireless applications. A wireless means of actuator excitation, communication, and sensor interrogation has many benefits such as fast inspection, less downtime, labor cost reduction, etc. Since microwave power transmission (MPT) has been first initiated from the concept of solar power satellites [1], it has been used and proposed for various applications such as a microwave-powered helicopter [2], a solar power satellite that converts solar energy to microwaves and beams down to the earth [3, 4], a 4.5 m wingspan airplane powered only by microwave energy [5], and a microwave-powered smart material actuator [6]. The key component for this type of wireless power transmission is rectenna. Rectenna is a combination of a rectifying circuit and an antenna. Rectenna converts microwave or RF power to dc power. The antenna receives the electromagnetic power and the rectifying circuit converts it to dc power. The rectifying circuit consists of a Schottky barrier diode, an inductor, and a capacitor. There are several types of rectennas, such as patch, dipole, bow-tie and slot [7-9]. Recently, a dual-polarized rectenna was developed that can produce a 50-V output voltage and can be used for driving smart material actuators [10].

Electro-Active Polymer (EAP) materials are able to offer a range of performance and characteristics that are promising for biologically inspired actuators. Many EAP materials have been so far developed [11]. Due to their characteristics, these materials have advantages and disadvantages, for example, high actuation voltage for electronic EAP materials and wetness requirement for ionic EAP materials. Recently, cellulose has been discovered as a smart material that can be used as sensors, actuators and smart devices. The newly discovered material is termed as electro-active paper (EAPap) [12], which has merits in terms of light weight, flexible, dryness, biodegradable, low electrical power consumption and low price. To overcome the durability and low actuation performance of EAPap at low humidity condition, many attempts have been made including a polypyrrole and ionic liquid nanocoating on the cellulose EAPap [13].

Once the MPT technology is integrated with the cellulose EAPap, a ultra-lightweight actuator can be developed since the integrated device does not need to carry battery so it can be a wirelessly-driven ultra-lightweight actuator. This paper aims at demonstrating a rectenna integrated EAPap actuator. However, there are technical challenges for the integration of rectenna and EAPap actuator. Firstly, the rectenna should be flexible so as to be integrated on the cellulose EAPap. Conductive antenna layer for the rectenna should be fabricated on the cellulose membrane and the Schottky diode should be soldered on the antenna. Secondly, the rectenna should be polarization independent with respect to the microwave antenna. Generally, dipole rectenna has high conversion efficiency while patch rectenna has low efficiency. However dipole rectenna is sensitive to its polarization: once its polarization is not matched with the microwave transmitting antenna, its efficiency is low [14]. Thus, a patch rectenna that has dual polarization is used in this research. This patch rectenna is insensitive to the polarization. The configuration, fabrication process and characterization of the patch rectenna are addressed, and the integrated rectenna-cellulose EAPap actuator is demonstrated.
2. Experimental

2.1 Design of patch rectenna

Fig. 1 shows a schematic diagram of the patch rectenna that consists of a ground layer with slot and a rectifying circuit layer with an independent rectifying circuit for each of two orthogonal polarizations. A dielectric substrate separates these two layers. The cross section of the rectenna is shown in Fig. 1(b).

![Schematic of patch rectenna.](image)

The patch rectenna was made on two different substrates for their performance comparison: flexible printed circuit board (FPCB) and cellulose EAPap [15]. FPCB is a polyimide membrane on which copper layers are laminated on both sides. Thickness of the polyimide layer of FPCB is 20 um and the copper layer is 18 um thick. Thickness of the cellulose membrane is 19 um (±5%). Relative dielectric constant of the polyimide is 3.48 at 2 GHz and the cellulose membrane is 14.0 over 1 MHz. Two layers in terms of the ground layer and the rectifying circuit layer are separated with the polyimide for the FPCB and the regenerated cellulose for the cellulose membrane. The rectifying circuit consists of Schottky diodes and microstrip line as a transmission line. An independent rectifying circuit for each of two orthogonal polarizations is made to mitigate its polarization sensitive behavior of the rectenna. The schottky diode characteristic is one of important parameters to decide performance of the rectenna. We used MA2054-1141T model Schottky diode of M/A-COM that has upper 250 mV of forward voltage, 3 V of breakdown voltage and 10 mA of reverse current. Initially designed slot length and width are 7 mm x 0.8 mm.

2.2 Fabrication of patch rectenna

Patch rectennas were fabricated on two different substrates. Thus, two different fabrication processes were provided: an etching process was conducted for the FPCB substrate and a silk screen printing process for the cellulose membrane. Fig. 2 shows the fabrication processes.

![Rectenna fabrication process.](image)
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and 5 µm, respectively, and these values of the cellulose and the silver layer are 14 µm and 7 µm.

Fig. 3. Photographs of Patch Rectennas: (a) Fabricated on the FPCB; (b) fabricated on the cellulose membrane.

Fig. 4. SEM images of patch rectennas: Surface image of (a) fabricated on the FPCB; (b) cellulose membrane and Cross section image of (c) fabricated on the FPCB; (d) cellulose membrane.

2.3 Experimental setup

An experimental setup for the MPT test of the patch rectenna is shown in Fig. 5. The MPT test was performed in an anechoic microwave chamber to protect against ambient noise. Microwave power was generated from a transmitter (ATV transmitter, GIE TV inc) and propagated through a waveguide and fed to a horn antenna (U-3000L, ED Laboratory) which gain is 15.13 ~ 17.82 dB depending on the frequency from 8.2 to 12.4 GHz. The microwave signal irradiated to the patch rectennas through the horn, and a dc power was obtained due to the rectifying circuit. A pulse signal analyzer (B&K 3560-B-030) was used to measure its output voltage and current of patch rectenna with 10 KΩ load resistor. The propagated microwave power is 1.2 W with 10 GHz.

Fig. 5 also shows the bending actuation test setup to demonstrate the possibility of the rectenna integrated EAPap actuator as a microwave driven actuator. Since the cellulose rectenna is made on cellulose EAPap, it can be the rectenna integrated EAPap actuator. Cellulose rectenna was located 10 cm far from the horn antenna and displacement sensor was located on the opposite side. Bending displacement was measured at the lower end of the cellulose EAPap.

Fig. 5. Schematic of microwave power transmission test setup.

3. Results and Discussion

3.1 Output power of patch rectenna

The performance of patch rectenna should be tested depending on the distances between the horn antenna and the rectenna as well as its incidence side. Fig. 6(a) and (b) show the dc voltage obtained from the FPCB rectenna when the microwave is incident on the ground layer side and the rectifying circuit layer side. When the microwave is incident on the rectifying circuit layer side, the MPT performance is better than the other side. As increasing the distance between the horn antenna and the rectenna, the dc voltage of the rectenna decreases, which is inversely

Fig. 6. Output voltages of patch rectennas with different polarization angles and when microwaves are incident to different sides: (a) ground layer of FPCB rectenna; (b) rectifying circuit layer of FPCB rectenna; (c) ground layer of Cellulose rectenna; (d) rectifying circuit layer of Cellulose rectenna.
proportional to the distance. Note that the cellulose rectenna shows higher dc voltage than the FPCB rectenna. The slot size effect of the rectennas is investigated. Table 1 shows the slot length. Fig. 7(a) shows the output voltage of FPCB rectenna with different slot length and polarization angle, and (b) represents the cellulose rectenna results. These patch rectennas are insensitive to their polarization. The slot length does not have significant effect on the performance of both rectennas. The cellulose rectenna shows higher dc voltage than the FPCB rectenna.

<table>
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<th>Table 1. Slot dimension of patch rectennas.</th>
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<td>Substrate</td>
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<tr>
<td>FPCB</td>
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<td>Cellulose membrane</td>
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Fig. 7. Output voltages of patch rectennas (10 kΩ load resistor) depending on different slot length and polarization angle: (a) FPCB rectenna; (b) cellulose rectenna.

3.2 Microwave driven eapap actuator

Fig. 8 shows the bending actuation test results of the rectenna integrated EAPap actuator by time sequence. Fig. 8(a) shows the output voltage of the rectenna. A rising time of the converted dc power at the patch rectenna is 1.6 sec, which might be associated with parasitic inductance and capacitance of the rectenna. Fig. 8(b) shows the bending displacement of the rectenna integrated EAPap actuator. The actuator moves to one direction when the power is on and recovers to its original position after the power off. When the power is on during 2 minutes, the maximum displacement of 2.2 mm is obtained. As the duration of the dc power-on time is reduced from 2 minutes to 0.5 minutes, its amplitude of the bending displacement decreases. To autonomously activate the actuator, a control circuit may be necessary that can control the signal and charge accumulation on the actuator so as to mitigate slow response. The addition of such control circuit may require additional dc power from the rectenna.

5. Conclusion

Flexible patch rectennas that are insensitive to their polarization were designed and fabricated on the polyimide substrate and cellulose membrane. The patch rectenna was designed with the rectifying circuit layer and the ground layer, in which a dielectric membrane separates these layers. The rectifying circuit layer consists of Schottky diodes and microstripline in such a way that the patch rectenna is insensitive to the polarization. Two dielectric substrates, namely FPCB and cellulose were used for the flexible patch rectenna fabrication. The etching process and the silk screening process were taken for these substrates. The output power of the cellulose patch rectenna was higher than the FPCB patch rectenna. The rectenna integrated EAPap actuator was tested by actuating with microwave. As the microwave power was on, the actuator bent, and the maximum displacement of 2.2 mm was obtained. This result shows the possibility of wireless EAPap actuation using microwave power. More investigation on the control circuit of the actuator is necessary.

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References

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