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Extending Applications of Dielectric Elastomer Artificial Muscles to Wireless Communication Systems

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1. Introduction

Electro active polymers (EAPs) are used for actuators that can electrically control their motions to resemble those of actual muscles. Thus, they are called artificial muscles. In addition, since EAPs are often made of flexible materials, they have also come to be called "soft actuators" in recent years. There are many types of EAPs such as dielectric elastomers (Perline & Chiba, 1992a), ionic polymer-metal composites (Oguro et al., 1999), electroconductive Polymers (Otero & Sansinera, 1998), and ion polymer gels (Osada et al., 1992b). Figure 1 shows typical EAPs.

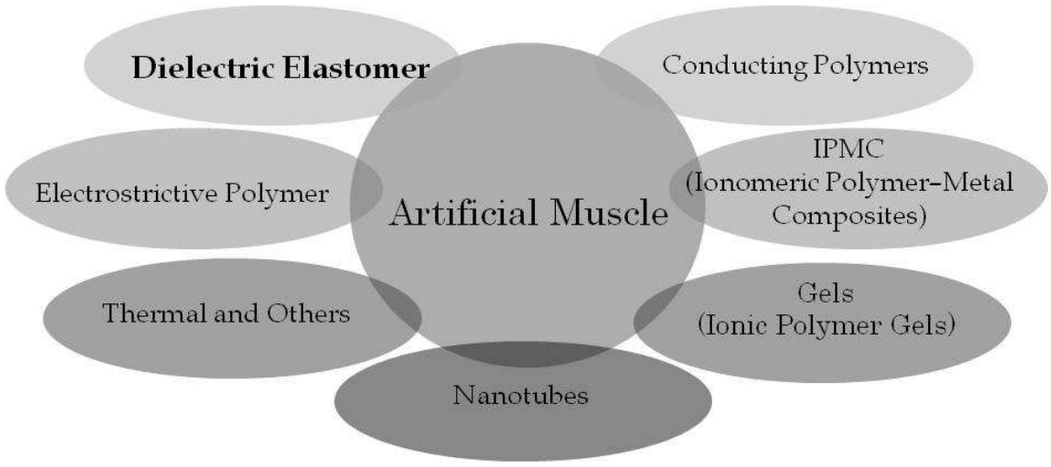


Fig. 1. Typical electro active polymers (EAPs)

EAP can be generally classified into two categories: elctrochemical polymers and fileld activated polymers (Kornbluh et al., 2004a). Electrochemical polymers use electrically driven mass transport of ions or electrically charged species to effect a charge in the shape (or vice versa). Field-activated polymers use an electric field to effect a shape change by acting directly on charges within the polymer (or vice versa). Each type of EAP has advantages and disadvantages for the application to wiress communications. Electrochemical polymers

typically can exert relatively high pressures and can be driven by low voltages. However, they are relatively slow and limited in size (since they are dependent on molecular trnasport), require high current and relatively energy inefficient. They can operate best over a narrow range of temperatures and must often be kept moist (Kornbluh et al., 2004a). In contrast, field-activated polymers can be fast, efficient ,and relatively insensitive to temperature and humidity fluctuations. These polymers can operate at relatively high voltages and low currents, that usually requires additional voltage conversion components but makes the size and capacity of wires and interconnects lighter and less ctritical (Kornbluh et al., 2004a).

A type of field-activated EAP transducer that embodies the desirable proprties of polymer is dielectric elastomers (Pelrine et al., 2000).

Dielectric elastomer is a new transducer technology uses rubber like polymer (elastomer) as actuator materials. They have been gaining attention as technologies that have reached the practical use level as actuators and even as devices that can generate electricity efficiently (Chiba et al., 2008a).

The present paper examines the possibilities of frequency-variable antennas that utilize the actuator mode of dielectric-type artificial muscles, and sensor networks that utilize this electric generator mode (Chiba et al., 2007a; Chiba et al., 2008a).

2. Background on dielectric elastomer artificial muscles

Dielectric elastomer is a new smart material with characteristics and properties not seen in other materials. The basic element of dielectric erastomer is a very simple structure comprised of thin polymer films (elastomers) sandwiched by two electrodes made of a flexible and elastic material, and can operate as an electric control actuator.

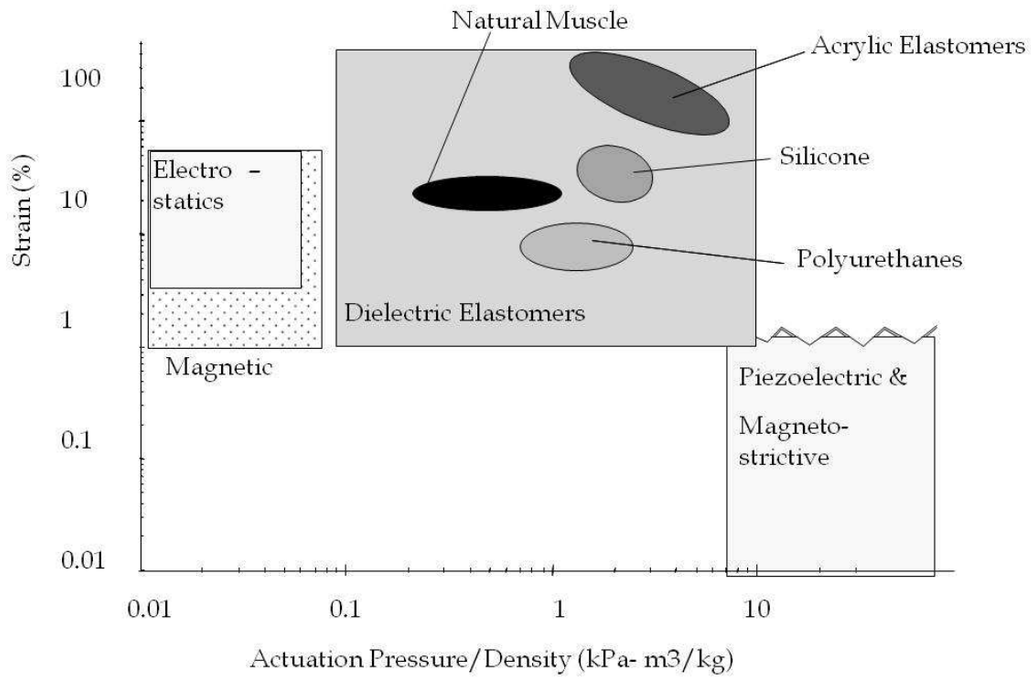


Fig. 2. Performance of dielectric elastomer is similar to that of natural muscle

Using a dielectric elrastomer actuator makes it possible to achieve a highly efficient transduction from electric energy into mechanical energy (the theoretical transduction efficiency is 80-90%, which translates into a considerable energy saving compared to other actuator technologies such as electric motors with gearboxes. At the material level, this material has fast speed of response (over 50,000 Hz has been demonstrated for small strains), with a high strain rate (up to 380% as shown in Photo 1), high pressure (up to 8 MPa), and power density of 1 W/g (for comparison, human muscle is 0.2 W/g and an electric motor with gearbox is 0.05 W/g) (Stanford et al., 2004a).
The energy density of dielectric elastomer has reached 3.4J/g, about 21 times that of single-crystal piezoelectrics and more than two oreders of magnitude greater than that of most commercial actuators (Pelrine et. al., 2000a). As can be seen in Figure 2, dielectric elastomers not only outperform existing actuator technologies in various areas but also are similar to natural muscle in that they fill the "actuator gap" between other actuation technologies, (Chiba, 2002). That is, dielectric elastomers have an actuation pressure/density that is bigger than that of electrostatic actuators and magnetic actuators, and cause strains that are bigger than that of piezo electric actuators and magneto strictive actuators.

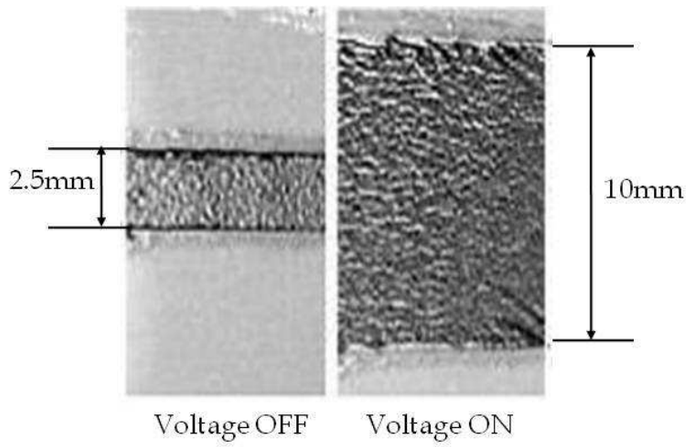


Photo 1. Acrylic elastomers showing 380% linear strain

2.1 Principle of operation of dielectric elastomers

Dielectric elastomer tranducers are based on the electromechanical response of an elastomeric dielectric film with compliant electrodes on each surface. Actuators based on dielectric elastomers technology operate on the simple principle shown in Figure 3. When a voltage is applied across the compliant electrodes, the polymer shrinks in thickness and expands in area.
The net volume change of the polymer materials that we investigate is small because of their high bulk moduli. Therefore, the electrodes must be compliant, to allow the film to strain. The observed response of the film is caused primarily by the interaction between the electrostatic charge on the electrodes. Simply put, the opposite charges on the two electrodes attract each other, while the like charges on the electrodes repel each other. Using this simple electrostatic model, we can derive the effective pressure produced by the electrodes on the film as function of the applied voltage. The pressure, ρ, is

$$\rho = \varepsilon \varepsilon_o E^2 = \varepsilon \varepsilon_o (V/t)^2 \quad (1)$$

where $\varepsilon_{o \text{ and}}\ \varepsilon$ are the permittivity of free space (8.85 x 10^{-12} F/m) and the relative permittivity (dielectric contact) of polymer, respectively; E is the applied electric field in V/m; V is the applied voltage; and *t* is the film thickness. The response of the polymer is functionally similar to that of electrostrictive polymers, in that the response is directly related to the square of the applied electric field,

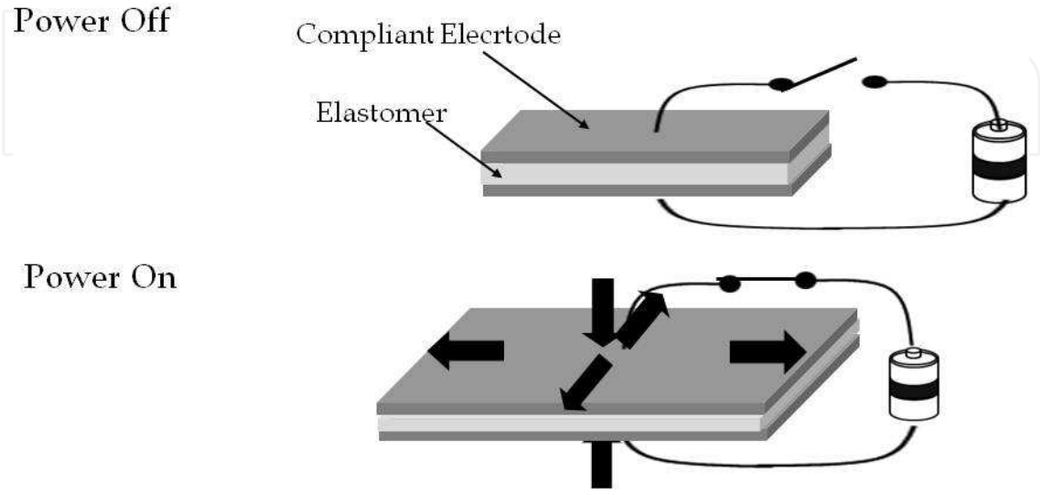


Fig. 3. Principle of operation of dielectric elastomers

Two observation made from Equation 1 clarify the difference between Maxwell stress actuation and the use of conventional air-gap electrostatic actuators. First, ε for polymers is typically in the range 2-12, whereas for air ε is 1. Thus the actuation pressure is increased substantially via polymers rather than air the same electric field. Another difference is that typical air-gap actuators have an additional factor of 0.5 in their equivalent pressure expression, i.e., the polymers double the actuation pressure independent of the dielectric constant. The reason for this difference is that the polymers can stretch in area rather just contract in thickness. Polymers have two modes of converting electrical to mechanical energy. In contrast to polymers, air-gap actuators are typically made of rigid materials that can convert electrical to mechanical energy via only one mode of motion, such as the convergence of opposite electrodes.

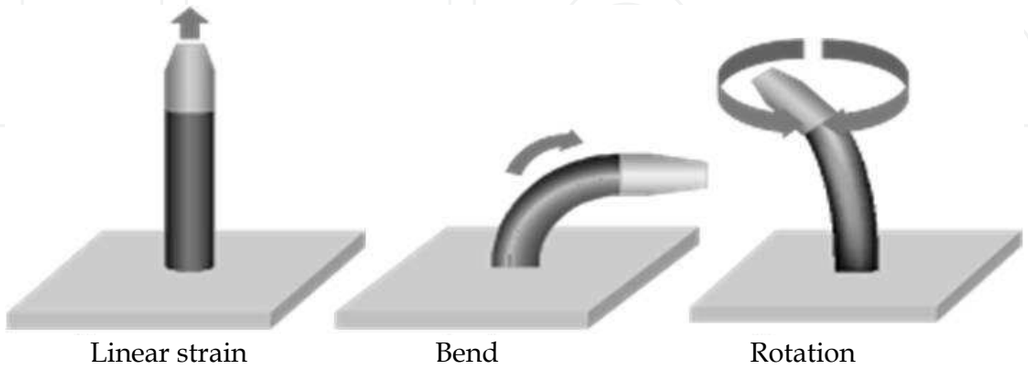
Dielectric elastomers also have other advantages over air-gap electrostatic actuators, even though both are based on electrostatic force. Several polymers have been identified with breakdown strength of 300 MV/m or more in thin films, but breakdown strength this high are difficult to achieve consistently in air-gap electrostatic devices.

As mentioned above, the three effects, i.e., "two-mode coupling," "high dielectric susceptibility," and "high electric strength," greatly contribute to the actuation pressure of the dielectric elastomers.

2.2 Development summary of dielectric elastomer actuators

The elastomer has excellent workability which enables the shape design of devices with sizes from micrometers to several meters. Also, as elastomers are light and deform like rubbers, they can show flexible movements like bionic actions. They can express "flexible and natural feeling" which systems with motors cannot imitate. A wide array of proof-of-

principle devices for use in leg robots (see Fig. 4), swimming robots, snakelike robots, compact inspection robots, geckolike robots for climbing up perpendicular walls or across ceilings, and flying robots, as well as in achieving compatibility with living organisms are currently developed (Stanford et. al., 2004b). The main feature of the dielectric elastomers is that they do not use any gears and cams, thus enabling high efficiency and safe and smooth driving even if the speed or direction of movement are suddenly changed.



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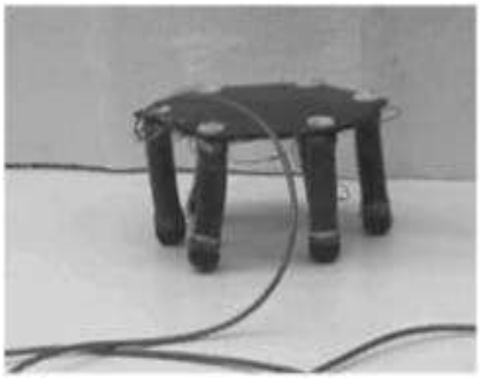


(b)

Fig. 4. Biologically inspired robots powered by dielectric elastomer rolls (Pei et al, 2003; Chiba et al, 2006a). (a) Role Actuator Having 3-DOF (b) Application example to a robot: it enables sideways stepping like a crab without turning around, when it collides with wall

The 3-DOF actuator may be used as actuator for variable antenna of wireless communication device (see section 3 "Proof-of-principle experiment on a frequency-variable antenna utilizing the actuator mode of dielectric-type artificial muscles").
Moreover, as this actuator has a wide dynamic range (DC to several tens of kHz), its applications to speakers and vibrational devices have been advanced (see Fig. 5) (Chiba et al., 2007a).
This device may be suitable for vibrators and speakers of wireless communication devices.
In addition, as there is a direct proportionality between the change in the capacitance and elongation of dielectric elastomer actuators, they can be used for pressure- and position-sensors (see Fig. 6). It may be possible to use the sensor function of dielectric elastomers to pick up electric waves for wireless communication devices.

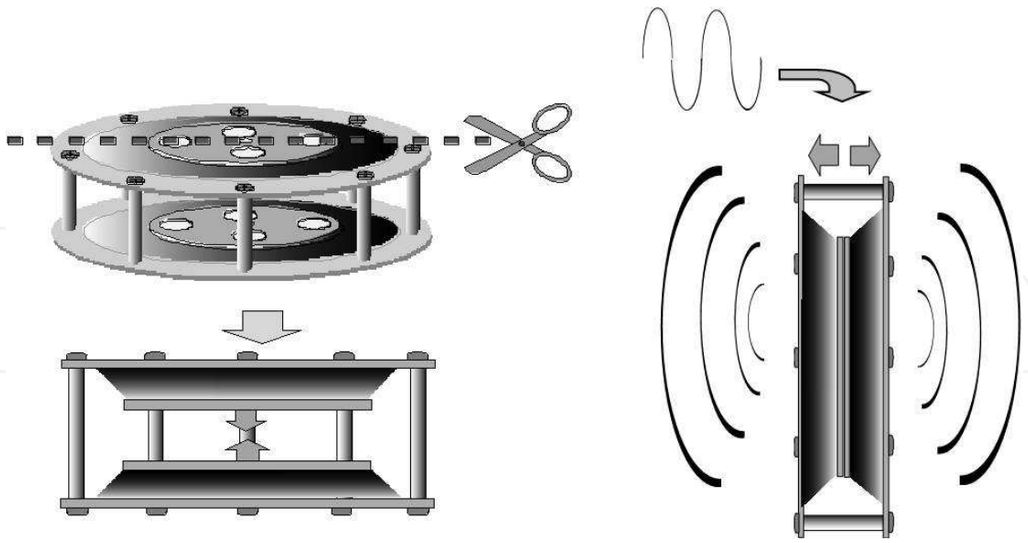


Fig. 5. Structure of speaker using dielectric elastomer (The black shaped part is dielectric elastromer) (Chiba et al., 2007a)

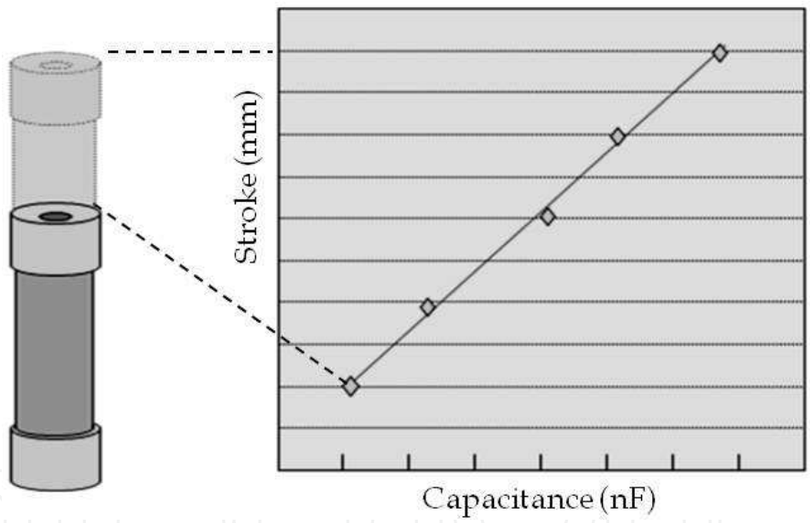


Fig. 6. Linear relation between capacitance and stroke of actuator (Kornbluh et al., 2004b)

3. Proof-of-principle experiment on a frequency-variable antenna utilizing the actuator mode of dielectric-type artificial muscles

The popularization of mobile telephones has brought wireless technology even closer to our daily lives. In recent years, improvements in integrated technology of electronic circuits and the increasing multi-functionality of mobile terminals have led to the inclusion of a multitude of diverse formats such as 3GPP, wireless LAN, Bluetooth, digital TV, etc., in single mobile communication devices. Since these communication formats all use different frequencies, it is necessary either to install a separate antenna for each wavelength, or use one antenna that can accommodate multiple frequencies.

Methods to create an antenna that is compatible for multiple frequencies include integrating antenna elements that can respond to multiple frequencies, and using an antenna that is shaped so that it can tune to a broad range of frequencies. The easiest method is to change the length of the antenna element, but because this changes the length of the antenna device, it requires equipment such as motors and gears. This makes it difficult to use as a small, lightweight frequency-variable antenna.

One way to resolve these problems may be to create a lightweight frequency-variable antenna with a simple structure by utilizing dielectric-type artificial muscles in the actuator part of a variable antenna.It may be possible to change the position of the reflection element and/or changing the length of dipolar- or monopolar antenna elements. Furthermore, by forming this structure onto polymers, it is possible to create a changeable-type planar antenna that can be installed in small, lightweight portable devices.

The present experiment corroborated the possibility of creating such variable-type antennas by using artificial muscle to change the length and tuning frequency of a monopolar antenna.

The variable-type monopolar antenna used in this experiment had a very simple structure. It was composed of a radial section that was attached to the dielectric artificial muscle actuator, and an antenna element section that was installed vertically on the core. (see Photo 2)

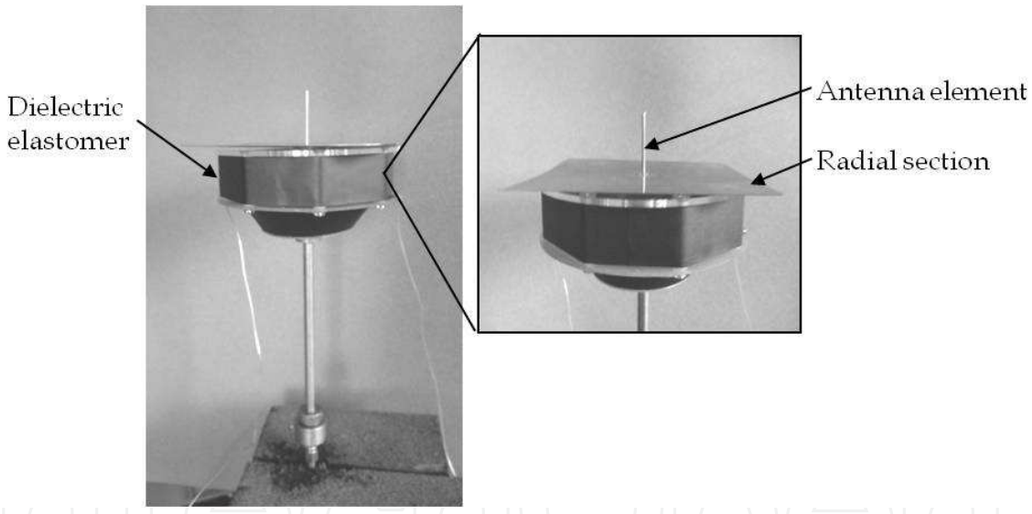


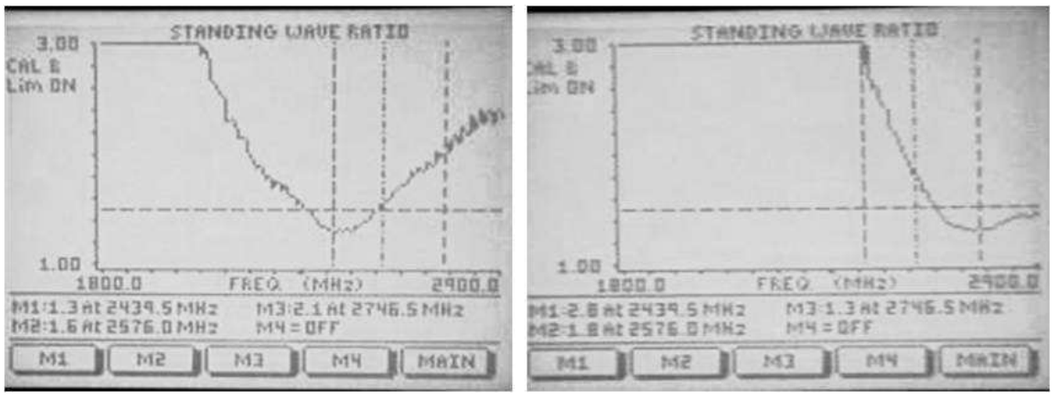
Photo 2. A frequency-variable antenna utilizing the actuator mode of dielectric elastomer artificial muscles

By changing the control voltage that was applied to the artificial muscle, a structure was created in which it was possible to change both the length of the antenna element part that was thrust out from the radial section and the tuning frequency.

In actuators that use dielectric artificial muscles, a thin (0.05 mm) elastomer film was attached to a 10 cm-diameter circular frame. By attaching two of these elastomers onto this frame, it became a diaphragm type with the cores of the elastomers attached to one another. The total weight, including the structural parts, was about 20 g.

The frequencies used in the experiment were in the 2.45 GHz band that is currently used in 3GPP, wireless LAN, and so on. The length L of the monopolar antenna element at a frequency of 2.45 GHz was 1/4 of the wavelength λ (122.4 mm), or 122.4/4 = 30.6 mm, and

the changeable width of the actuator was 4 mm. This made it possible to change the tuning frequency within a range of about 300 MHz.
The change in the tuning frequency was confirmed by measuring V. S. W. R. (Voltage Standing Wave Ratio) using a network analyzer (Photo 3).



(a) Before change (b) At the time of the maximum change

Photo 3. Measurement of V. S. W. R. (The setting frequency range of a network analyzer: start frequency, 1.8 GHz and stop frequency, 2.9 GHz)

In this experiment, a diaphragm actuator for artificial muscle speakers was used, but this system was not smart, because the muscle part was too large. However, since the purpose of this experiment was to make the resonant frequency of a non-directional antenna variable by changing the length of the antenna element, a monopole antenna, which has the simplest structure, and artificial diaphragm muscles were used.
In our next experiment, we plan to change the direction of electric wave radiation by varying the installation angle of a directional antenna with roll-type artificial muscles.
In another words, the plan call for conducting an experiment to vary the directivity inside the vertical face of the antenna by making a model (ground plane) antenna by changing the wire in the radial part, and enabling the angle of attachment to the radial part to be changed by the roll-type artificial muscle. If such a variable antenna can be put to practical use, then it might be possible to create a system where the antenna can automatically be varied to match a more optimal electric wave environment, and even a small amount of electric power can be used to construct a suitable electric wave environment.
Furthermore, plans are being drawn for conducting an experiment on a planar antenna whose directivity and tuning frequency can be changed by using the dielectric-type artificial muscle to transform the antenna formed on the polymer. In the near future, by using variable antennas whose shape changes to match the use in mobile telephones, personal computers, etc., it may be possible to create a pleasant wireless communications environment with just a little bit of electrical power.

4. Sensor network that utilizes the power generation mode of a dielectric elastomer artificial muscle

Another working mode of the dielectric elastomer artificial muscle is the power generation mode. This is operatively the opposite of the actuator function. By adding external power to the dielectric type artificial muscle, the shape can be changed, and the increased static

electrical energy produced therefrom can generate electricity. Since this power generation phenomenon is not dependent on the speed of transformation, its power generation device can generate electric energy by utilizing natural energies such as up-and-down motions of waves, slowly flowing river water, human and animal movements, and vibration energies produced from vehicles and buildings.

4.1 Principal of the power generation mode

The operation principle in the generator mode is the transformation of mechanical energy into electric energy by deformation of the dielectric elastomer (Ashida et al,:2000b). Functionally, this mode resembles piezoelectricity, but its power generation mechanism is fundamentally different. With dielectric elastomer, electric power can be generated even by a slow change in the shape of dielectric elastomer, while for piezoelectric devices impulsive mechanical forces are needed to generate the electric power. Also, the amount of electric energy generated and conversion efficiency from mechanical to electrical energy can be greater than that from piezoelectricity (Chiba et al,. 2007a). Fig.7 shows the operating principal of dielectric elastomer power generation.

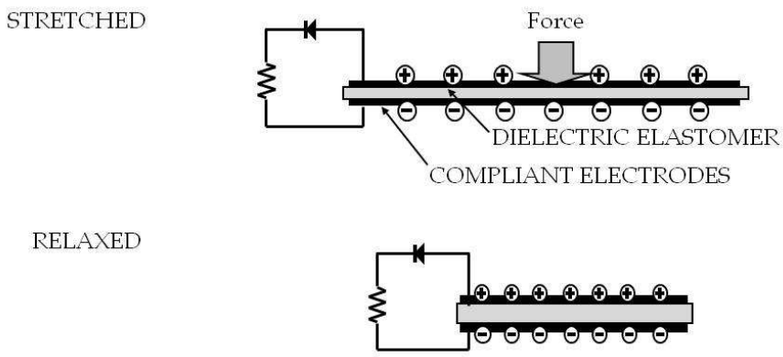


Fig. 7. Operating principle of dielectric elastomer power generation

Application of mechanical energy to dielectric elastomer to stretch it causes compression in thickness and expansion of the surface area. At this moment, electrostatic energy is produced and stored on the polymer as electric charge. When the mechanical energy decreases, the recovery force of the dielectric elastomer acts to restore the original thickness and to decrease the in-plane area. At this time, the electric charge is pushed out to the electrode direction. This change in electric charge increases the voltage difference, resulting in an increase of electrostatic energy.

$$C = \varepsilon_0 \varepsilon A/t = \varepsilon_0 \varepsilon b/t^2 \quad (1)$$

where ε_0 is the dielectric permittivity of free space, ε is the dielectric constant of the polymer film, A is the active polymer area, and t and b are the thickness and the volume of the polymer. The second equality in Equation (1) can be written because the volume of elastomer is essentially constant, i.e., $At = b$ = constant.

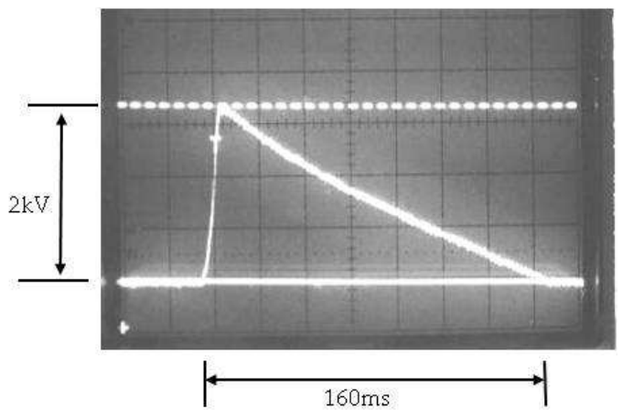
The energy output of a dielectric elastomer generator per cycle of stretching and contraction is

$$E = 0.5 C_1 V_b^2 (C_1/C_2 - 1) \quad (2)$$

where C_1 and C_2 are the total capacitances of the dielectric elastomer films in the stretched and contracted states, respectively, and V_b is the bias voltage.
Considering then changes with respect to voltages, the electric charge Q on a dielectric elastomer film can be considered to be constant over a short period of time and in the basic circuit. Since $V = Q/C$, the voltages in the stretched state and the contracted state can be expressed as V_1 and V_2, respectively, and the following equation is obtained:

$$V_2 = Q/C_2 = (C_1/C_2)\ (Q/C_1) = (C_1/C_2)\ V_1 \tag{3}$$

Since $C_2 < C_1$, the contracted voltage is higher than the stretched voltage, corresponding to the energy argument noted above. The higher voltage can be measured and compared with predictions based on the dielectric elastomer theory. In general, experimental data based on high impedance measurements are in excellent agreement with predictions. When the conductivity is assumed to be preserved in the range of electric charging, Q remains constant.



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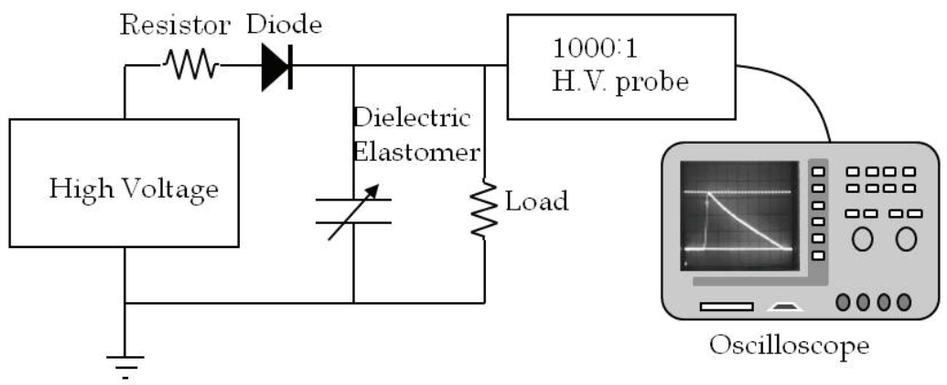


(b)

Fig. 8. Voltage for compression of dielectric elastomer and measurement circuit. (a) Typical scope trace from contraction of dielectric elastomer. Voltage spike occurs at contraction and gradually back to (stretched) voltage due to load resistance. (b) Measurement circuit of generated energy

Figure 8(a) shows a typical scope trace from contraction of dielectric elastomer. Figure 8(b) shows a simplified circuit for oscilloscope measurement of voltage. The voltage peak generated for one cycle is typically on the order of a few ms to several tens of ms for a piezoelectric element. However, in the case of dielectric elastomer, the peak width is on the order of 150-200 ms or longer (Chiba et al., 2008a). The long power-generation pulse duration of dielectric elastomer can allow for the direct use of generated energy for activities such as lighting LEDs. This can even power wireless equipment that is evolving today at a rapid pace. In continuous cyclical motions, it is easy to continuously obtain electrical energy by using flat and smooth circuits, even with gentle kinetic energy below a few Hz (Chiba et al., 2007b)

4.2 Application of dielectric elastomer generator to wireless communication system

In a power generation experiment, a thin artificial muscle film (25 cm long x 5cm wide, weight about 0.5 g) attached a human arm was able to generate 20 mJ of electrical energy with one arm movement. It is also possible to make them generate electricity putting up dielectric elastomers besides the arm to the side and the chest of the body (See Fig. 9a).

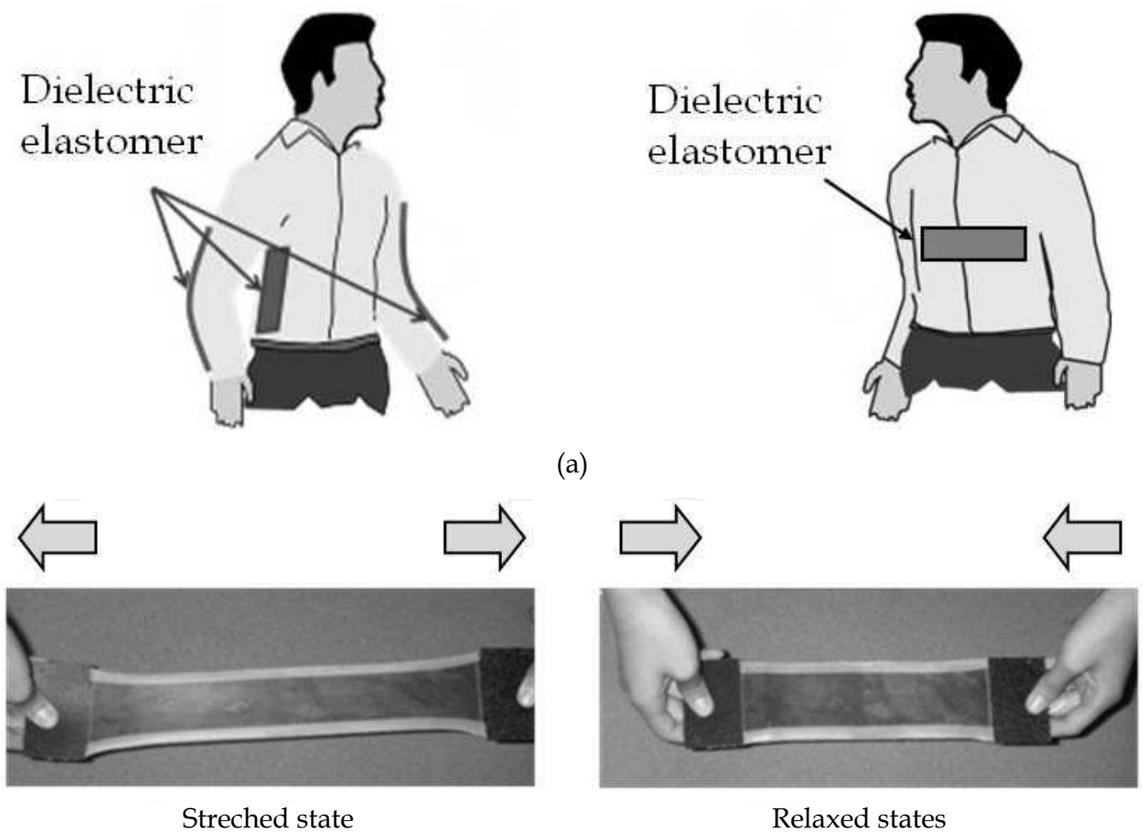


Fig. 9. Harvesting energy system from human body. (a) Conceptual rendering of dielectric elastomers put up to side and chest of arm and body: (b) Stretched state of dielectric elastomer (left) and Relaxed state of the elastomer (right)

Furthermore, in an experiment using different power generation equipment, artificial muscle film attached to the bottom of a shoe was verified to generate electricity when the artificial muscle was distorted while walking. When an adult male took one step per second, one shoe was able to produce about 1 W of electrical power. (Harsha et al., 2005)

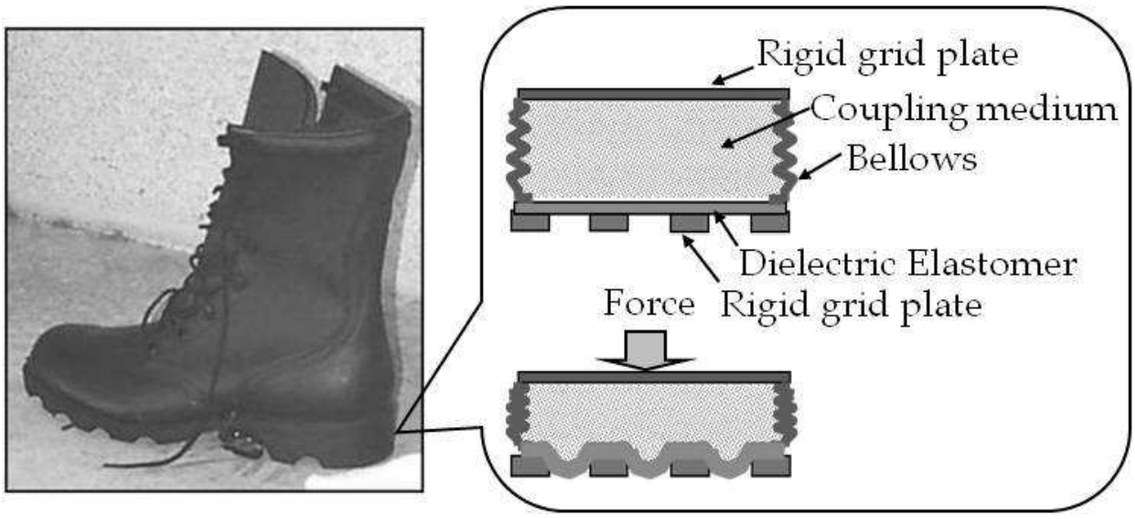


Fig. 10. Shoe generator

This confirmed that by utilizing human movement, enough electrical power could be obtained to recharge batteries for mobile telephones and similar devices (Chiba et al., 2008). In addition, electrical energy from the movements of animals could be used to construct livestock management systems. Other applications of animal-generated energy being investigated include scientific surveys of ecosystems of migratory birds and fish, among others.

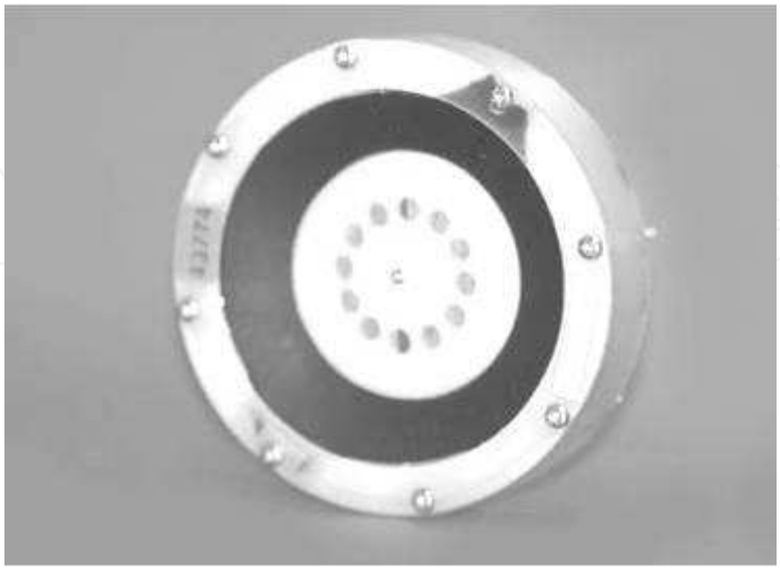
In an experiment using a diaphragm actuator, electrical power output of about 0.12 – 0.15W was obtained by pressing the center of a roughly 1 g, 8 cm-diameter EPAM a few millimeters one time per second (Chiba et al., 2007a). Using the same equipment, the electric power generated was able to illuminate 6 LEDs, and by combining this with a wireless system, it became possible to turn a device on and off from a remote location.

In such ways, dielectric elastomer artificial muscles can supply electrical power only when mechanical energy is obtained, and it is possible to simultaneously act as a switch that detects power sources and motion. Consequently, it may possible to easily create wireless networks, with simple components that do not require batteries (Chiba et al., 2007a).

In recent years, global warming and accompanying abnormal weather have begun to have an impact on our daily lives. To protect ourselves from the disasters brought about by abnormal weather, it is important to thoroughly understand the current situation, that is, how the global environment is changing.

The monitoring of the global environment has been done by various countries on their own, but to monitor environmental changes on a global scale it will be necessary to build wide-ranging sensor networks. One of the major issues with that, however, is that there is no good method for obtaining electrical energy for running this system. Presently, many if not most of these sensor systems are powered by solar batteries, but in some locations and during some seasons the daylight hours are extremely short, and in maritime and desert

areas salt and dust can dramatically reduce the electrical output. All this makes it difficult to maintain a stable sensor system.



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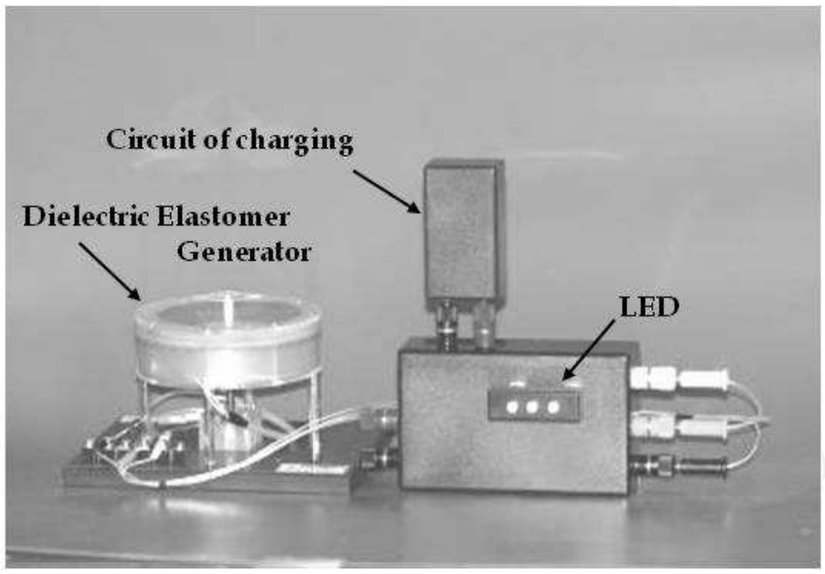

(b)

Photo 4. Small scale power generation device. a) Cartridge of used for small generator. The black ring-shaped part is dielectric elastomer. b) A power of approximately 0.12 W can be generated, by pushing the central part of dielectric elastomer by 3- 4 mm once a second

As one way of resolving these issues, power generation systems that utilize artificial muscles to generate power through transformation alone are attracting attention. Already, experiments using wave power to generate electricity have been able to produce a few watts of electrical energy with small artificial muscle power generation equipment loaded onto

weather observation buoys, (see photo 6 and fig. 11) and this has also been confirmed to recharge batteries (Chiba et al., 2009).

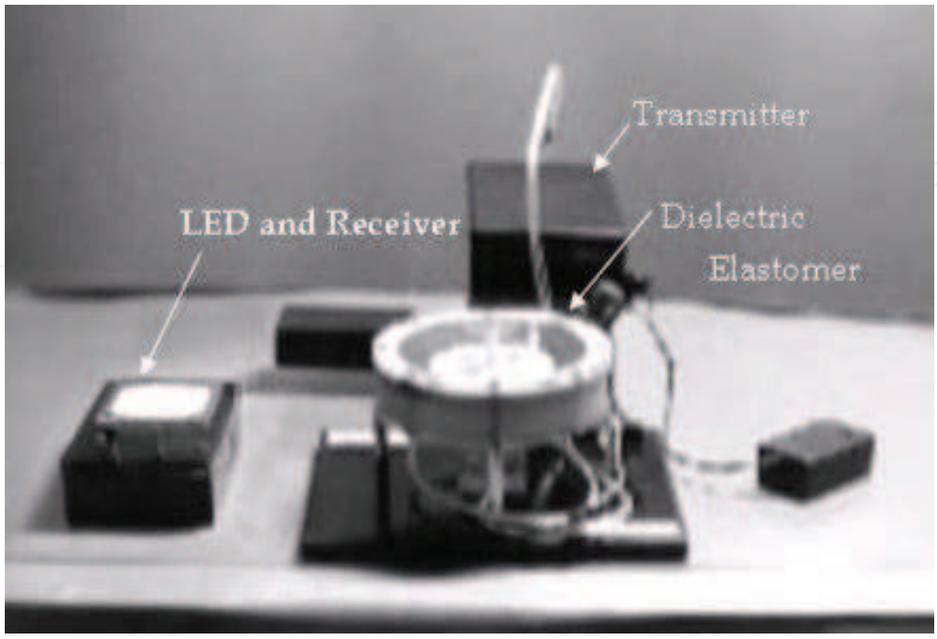

Photo 5. Small scale power generation device & LED controlled by wireless signals

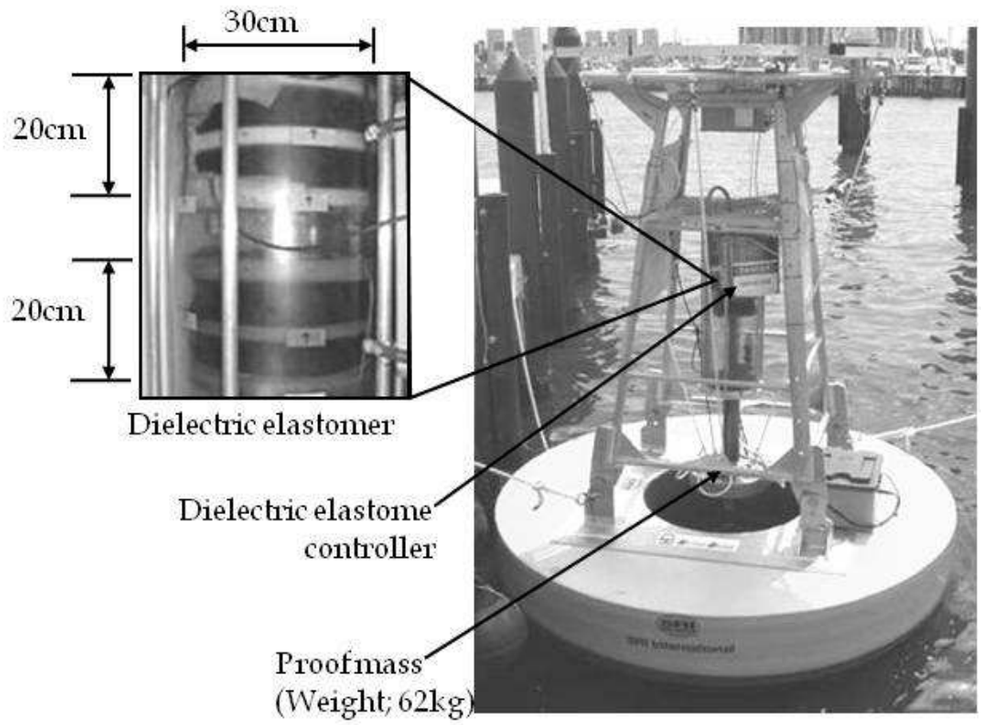

Photo 6. Dielectric elastomer generator on the test buoy

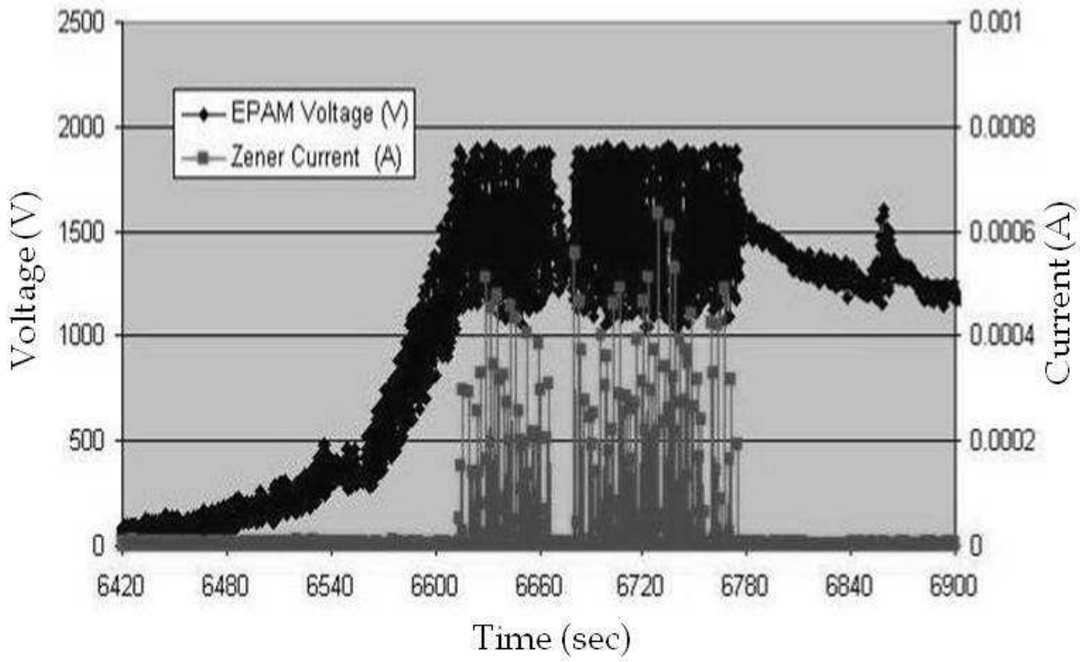

Fig. 11. Electricity generated by ten centimeter-high waves

In other experiments (see photo 7), electrical energy has been obtained from flowing water in a laboratory (Chiba et al., 2007a). The flow of water rotates the water-mill, and the rotational motion induces the deformation of the dielectric elastomer to generate electrical energy. Figure 12 shows the conceptual rendering of water mill generator using dielectric elastomer (Chiba et al., 2007a).

Furthermore, the results of simulations based on conceptual designs of flag-type power generation equipment using artificial muscles have indicated that there is little loss from the fluttering of flags and that it is possible to generate electric power with a high rate of efficiency (Chiba et al., 2007b).

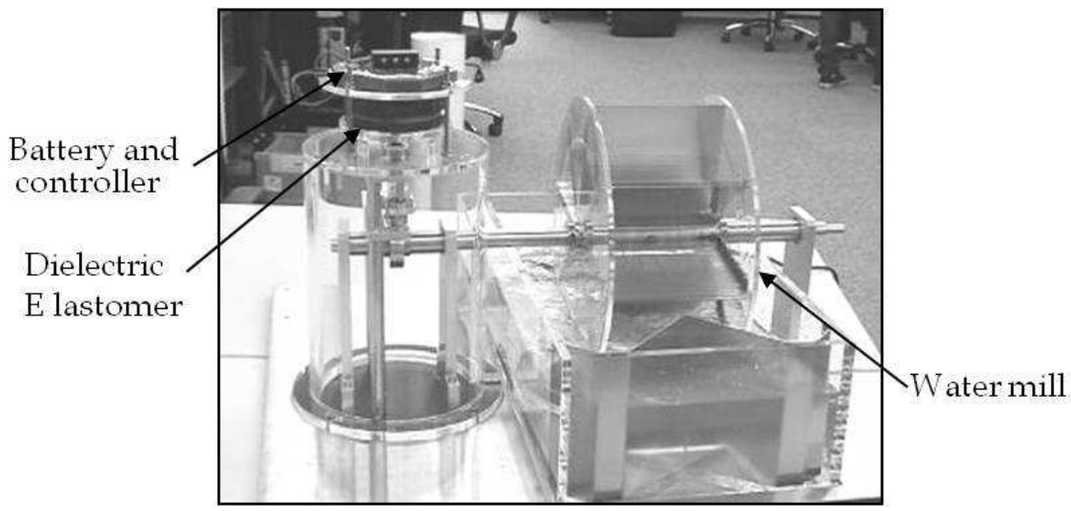

Photo 7. Water mill generator using dielectric elastomer

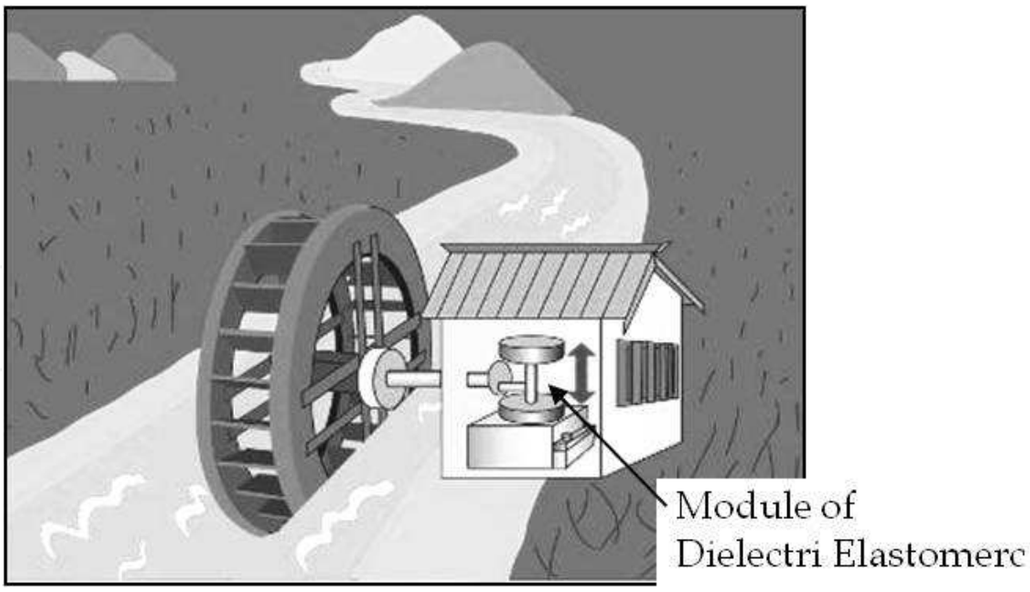

Fig. 12. Conceptual rendering of water mill generator using dielectric elastomer (Chiba et al., 2010)

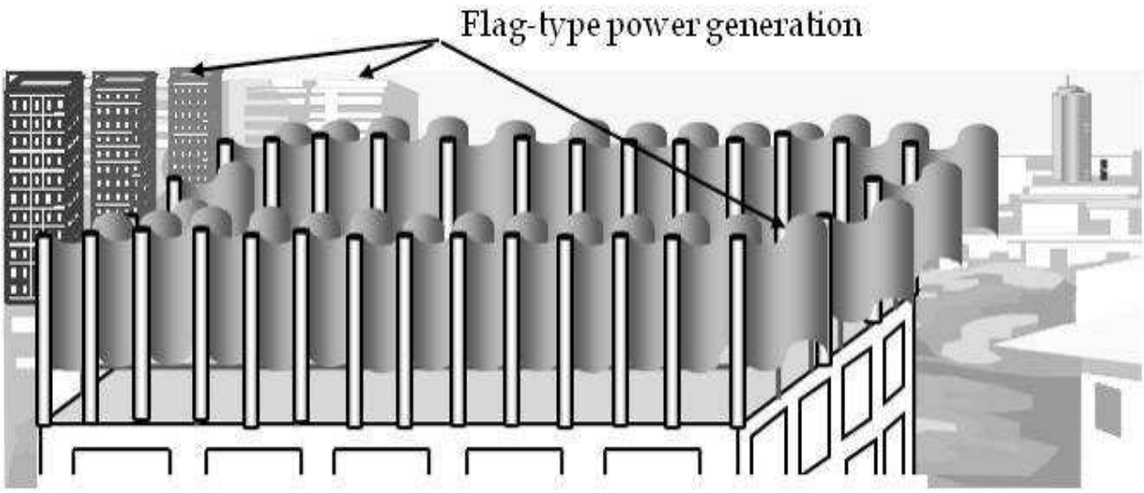

Fig. 13. Conceptual rendering of flag-type power generation

4.3 Analysis of power generation cost

Even without dielectric elastomer technology, ocean wave power is beginning to flourish in several countries. These ocean wave power systems typically use hydraulic pistons that are pumped by the wave action. The hydraulic fluid flows through a transmission and then a turbine to spin a rotary electromagnetic generator. When these systems are successfully developed for commercial use, the unit price of a power generation of kWh is estimated to be about 20 US Cents (Chiba et al., 2008b). These wave power systems are typically designed for ocean waves exceeding 2 - 3 m in height. At significantly smaller wave heights, the systems become less economically attractive (Miyazaki et al, 2007).

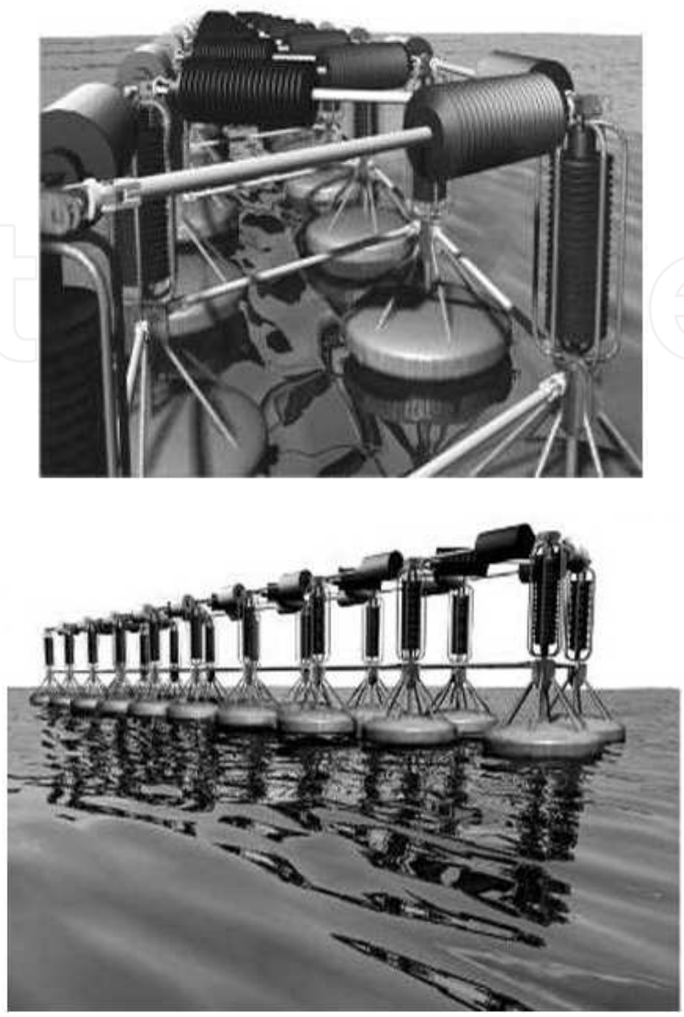

Fig. 14. Conceptual rendering of wave power generator system using dielectric elastomers

Because of its simplicity, efficiency, and size scalability, we believe that dielectric elastomer-based wave generator systems can be attractive not only for large wave applications but for many applications where the waves are much smaller. An estimate based on data from our sea trial demonstration experiments has shown that even in seas where the wave height is only 1 m throughout the year (e.g., the sea close to Japan), if there are spaces of approximately 500 m in length and 10 m in width, the establishment of a sea-based facility generating 6 MW of power is possible (Chiba et al., 2008b). This is a useful amount of power, be it for general use or for providing energy for nearby residential or industrial needs. The ability to produce the power where it is needed can eliminate the losses and costs associated with power transmission over long distances and make wave power even more attractive. The power generation efficiency estimated on the basis of the data obtained from in-tank experiments in 2006 (Chiba et al, 2006b) and ocean demonstration experiments in 2007 (Chiba et al, 2008a) and 2008 (Chiba et al, 2009) is approximately 19 US cents/kWh. In the near future, we expect that the electric power generation per unit mass or volume of dielectric elastomer material can double, and that the expected power generation cost per

kilowatt-hour is 5 - 7.5 US cents. This value is comparable to that for fossil fuel thermal power plants. Of course, the wave power systems have the additional benefit of not releasing any pollution or greenhouse gasses.

5. Future of dielectric elastomer systems to wireless communication

The variable antenna technologies with artificial muscles have high expectations to apply to not only data communications for mobile phones and personal computers but also wireless sensor systems which monitor various data concerning weather conditions and environments. In the future, the combination of these artificial muscle power-generating systems with various sensing systems will make it possible to conduct sensing on a global scale, and may even make a significant contribution to the creation of systems that will protect human lives from natural disasters that have so far been difficult to predict.
Various power generating systems can be set up in each place on the earth as shown in Figure 15 in order to create wire sensor networks.

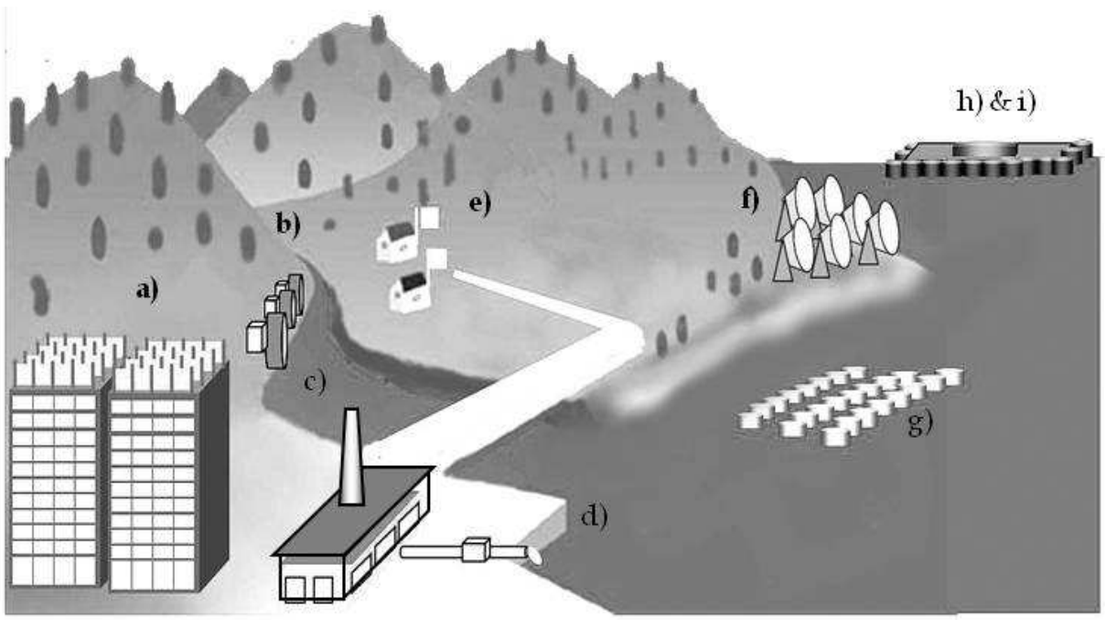

Fig. 15. Sites where power generation using dielectric elastomers is possible and conceptual rendering of the generation systems: (a) Wind Power Generator on tops of buildings (Chiba et al., 2007b) (b) Water Mill Generators (Chiba et al., 2007a) (c) Waste energy Generators (Chiba et al., 2011) (d) Drain Generators (Chiba et al., 2011) (e) Wind Power Generators for Personal Houses (f) Solar Heat Generators (Chiba et al., 2007b) (g) Wave Generators (Chiba et al., 2006; Chiba et al., 2008a) (h) Wave Generators in Ocean (Chiba et al., 2008a) (i) Hydrogen Production Plant (Chiba et al., 2008b)

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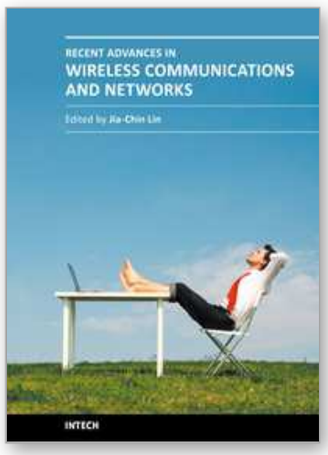

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This book focuses on the current hottest issues from the lowest layers to the upper layers of wireless communication networks and provides â€œreal-timeâ€ research progress on these issues. The authors have made every effort to systematically organize the information on these topics to make it easily accessible to readers of any level. This book also maintains the balance between current research results and their theoretical support. In this book, a variety of novel techniques in wireless communications and networks are investigated. The authors attempt to present these topics in detail. Insightful and reader-friendly descriptions are presented to nourish readers of any level, from practicing and knowledgeable communication engineers to beginning or professional researchers. All interested readers can easily find noteworthy materials in much greater detail than in previous publications and in the references cited in these chapters.

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