Remote power transfer using magneto-electric devices

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Abstract. We report remote power transfer using magneto-electric devices. The experiments were performed at room temperature for piezoelectric beam coupled with electromagnet. Neodymium magnet was used as mass loading. We observed the output power of the order +19.3 to -71.1 dB given the gap between the input and output source was varied from 4 mm to 12 mm for the device (21.3 mm×3.59 mm×0.57 mm) with best performance at the resonance peak. We tested the device for frequency sweeps of 10-100 Hz and 100-5000 Hz. This enabled us to figure out the output power for the device at resonant frequencies over a wide frequency range. The device has high input impedance (as opposed to coils) and can be miniaturized aggressively to below 100 µm linear dimensions. The piezoelectric beams have much higher quality factors (Q) larger than 1000 while coils have low Qs (~ 20) and the harvesting efficiency is proportional to Q.

1. Introduction

Coils are used to inductively power implantable devices. To reduce the size of the coils and associated components one needs to increase the signal frequency. It is well known that losses increase at higher frequencies and the power transfer efficiency reduces as given by Friis’s near-field magnetic formula (1). So it is desirable to have power transfer links operating at low frequencies that at the same time are smaller in size for implant applications. As long as the implantable part of the power link is made very small, the part that is outside the body can be as large as necessary. Here we discuss a device consisting of a piezoelectric beam integrated with a permanent magnet to convert acoustic and magnetic signals to electricity. This approach enables miniaturization of the implantable part of the power link down to micrometer size levels which otherwise is not possible with coils even at high frequencies. Moreover, the power transfer efficiency in resonant circuits also depends on the quality factors of its receiver/transmitter parts and piezoelectric resonant structures can easily achieve Q’s in excess of a few 1000 compared to 18 or 20 that can be achieved in the best inductors.

Powering wireless sensors in biomedical and consumer electronics has been a major driving force behind the significant research done in this area. Energy scavenging from radio waves [1-5], vibration [6-9], electric field generated by over-head power line [10-11], thermal gradient and photons has been reported using MEMS devices. Ashebo et al. [12] reported a concept to convert vibration energy from the bridges and pavements and obtained ~6 µW output power when subjected to an acceleration of 0.05 m/sec². Mongia and Abdelmoneum [13] proposed the conversion of heat energy 300-600 mW in
mobile platform when operated at 35-50 W thereby saving 1% of the input energy, using micromachined thermopile. Marzencki et al. [14] reported thin film AlN cantilever micro generator with power output of 0.038 μW from a 0.5 g vibration at 204 Hz resonant frequency. Marzencki et al. [15] increased the vibration to 4g at 1368 Hz resonant frequency to generate a power of 1.97 μW. Shen et al. [16], reported a PZT cantilever MEMS-based micro generator with power output of 2.15 μW for a vibration of 2 g (g = 9.81 m/s²) at resonant frequency of 461.15 Hz. Challa et al. [17] demonstrated output of 332 µW from a piezoelectric and electromagnetic coupled device.

In this paper we use a piezoelectric beam with a neodymium magnet to use magnetic field variations in addition to vibrations for power harvesting and transfer. It is also possible to add electrically “charged” regions as shown by Pai et al. [18] to enable electric fields powering as well. Apart from determining the amount of power available, we have also used isolated piezoelectric material to quantify energy available as a function of frequency. The ultimate aim is to develop a device that can be used to transfer maximum power from wireless devices, eliminating use of low Q MEMS coil. The objective of the paper is to determine the power transfer efficiency over a large frequency range.

2. Device fabrication and set-up

The amount of energy available in the environment is quite large but only a small portion of it can be converted to useful energy. Solar energy [19] alone can provide 15000 μW/cm² power density and 150 μW/cm² during cloudy conditions. This reduces to 6 μW/cm² indoors. The vibration energy on the other hand gives around 100-200 μW/cm², acoustic noise is around 0.003 dB, daily temperature variation can provide 10 μW/cm², and the temperature gradient in the surrounding accounts for 15 μW/cm² for 10 °C gradient. It is thus very important to understand how much energy can be detected and utilized by the energy harvesting devices. To demonstrate the same we used a set-up to excite the best device, which we obtained from section1, for further study. We used the Keysight (Agilent) Technologies 4395A Network/Spectrum/Impedance Analyzer for the study. The device, with the magnets and coils has been shown in the figure 1. The device was subject to different cases for the different frequency sweeps. For the 10-100 Hz sweep the case 1 was when input was applied to coil 1 and output was taken from coil 2. For case 2 the input was given to coil 1 and output was taken from PZT/magnet. In case 3 the input was applied to PZT/magnet and output from taken from coil 2.

![Fig. 1: Optical image of device, magnets and the coils used in the measurement of energy transfer.](image)

For the 100-5000 KHz sweep the cases were similar. The distance was measured from input to output/ (4 mm, 7 mm, and 12 mm). The bandwidth was 10 Hz, input power was 1 dBm (251 mV), input gain (RF Source) was 20 and the output gain (channel B) was 5. Figure 2 below shows the common set-up for all the cases. The input and output changed according to the case used.
3. Experimental Results

We examined 3 cases. In case 2 we used a coil as the primary and a PZT/magnet as the secondary (Figure 3). In case 3, we reversed the roles of the coil and the PZT/magnet and used the coil as the secondary and the PZT/magnet as the primary (Figure 4). We also used a coil-coil coupling (case 1) through air for comparison (Figure 1). When the PZT/magnet was used as the primary, the vibration of the magnet produced a time dependent magnetic flux density that induced an EMF in the receiving (secondary) coil. Our devices were fabricated using PZT beams (Figure 1) cut from PZT discs. The beams had fundamental resonance frequencies below 100 Hz (Figures 3 and 4) to enable harvesting environmental vibrational energy as well. Higher frequencies (100s of KHz) can be designed if needed for ultrasonic powering and communication.

The frequency sweep from 100-5000 Hz was very informative as it gave multiple peaks for higher frequencies. The gap range in this case was only taken as 4 mm, 7 mm and 12 mm between the input and the output source. The bandwidth was set to 10 Hz and the input power was 251 mV for all the cases.
The device had multiple peak resonances and that were reproducible in all the cases at ~230 Hz, ~370 Hz, ~737 Hz, ~1890 Hz, and ~3430 Hz. The best response was 15 dB at 786 Hz for case 2 at 4 mm gap and -51.9 dB at 737 Hz for case 3.

4. Calculations and discussion

The power transfer efficiency is higher (~50 %) at lower frequencies (100 Hz) as given by the Friis’s near-field magnetic field power formula:

$$ P_{RX(t)} = \frac{P_{RX}G_{TX}G_{RX}}{4} \left( \frac{1}{kr_x^2} + \frac{1}{kr_y^2} \right), $$

(1)

Where $P_{RX}$ is the received and $P_{TX}$ is the transmitted powers, $G_{TX}$ is the transmitter magnetic dipole gain, $G_{RX}$ is the receiver dipole gain, $k = 2 \pi / \lambda$ is the wave number with $\lambda$ the wavelength, and $r$ is the distance between the transmitter and the receiver.

The results for power transfer over different frequency ranges are shown in Figures 8a and 8b. Three different measurements were performed: a) coils were used to transmit and receive power, b) a coil generated time varying magnetic signals and the PZT-magnet was the receiver, and c) PZT-magnet generated the magnetic signal and a coil received it. The first case is not shown here but it can be used to communicate signals from the implantable device. The best result was obtained when we used a coil to generate the magnetic signal and the PZT-magnet to receive it. We note that it is more convenient to micro fabricate high-Q piezoelectric beams than coils that tend to be very lossy at micro-scale. Our work reported here introduces the possibility of using a PZT-magnet beam for...
communicating with implantable devices as well as powering it efficiently.

5. Conclusion
A new resonant power transfer/harvesting device consisting of a primary coil and a secondary PZT/magnet is discussed. The best power transfer efficiency (52%) was achieved at 786 Hz for output taken from the PZT beam at 4 mm gap between the coil and the beam. For the 10-100 Hz 19.3 dB (54% efficiency) was obtained at ~30 Hz for 2 mm gap between the input and output source. The receiving part of power transfer/harvester device discussed here can be fabricated with very small dimensions unachievable for coils. It can also have high quality factor improving the power transfer efficiency and can be used to harvest mechanical as well as magnetic field fluctuations in the environment.

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