# DEMONSTRATION OF A MICROMACHINED ELECTRODYNAMIC TRANSFORMER AND APPLICATION IN A RESONANT DC/AC POWER INVERTER

**S. Cheng and D. P. Arnold**
Interdisciplinary Microsystems Group, University of Florida, Gainesville, FL, USA

**Abstract:** This paper presents the fabrication and characterization of a two-port micro-electromechanical device that functions as an electrical transformer. The "electrodynamic transformer (ET)" uses a vibrating beam in a static magnetic field to transfer energy between the input and output electrical ports. We have previously reported macroscale (10 $cm^3$) proof-of-concept ET devices to demonstrate the fundamental physics and potential applications. Herein we report the first demonstration of 1000x smaller microfabricated devices (10 $mm^3$), achieving a power transfer efficiency of 40% with first-run prototypes. Additionally, an ultra-low-voltage dc/ac inverter based on the ET is demonstrated using only two external components—a MOSFET and a capacitor.

**Keywords:** electromechanical transformer, electrodynamic transducer, power converter, power inverter

## INTRODUCTION

Electromechanical devices, such as piezoelectric transformers, have shown promise for application as high-power-density, high-efficiency power converters [1-3]. These transducers usually consist of a cascaded actuator/generator set that bridges two electrical circuits, with mechanical motions serving as the energy transfer media between the electrical circuits. The advantage of using mechanical motion as the energy transfer media, as opposed to magnetic flux in conventional electromagnetic transformers, is the potentially higher "power throughput" per unit of device volume. This is partially due to the fact that the physical limit of the mechanical energy density in a mechanical structure is typically orders of magnitude higher than that of the magnetic energy density in a magnetic core. Another reason is that the fabrication technology that miniaturizes mechanical structures is more mature than for magnetic cores.

Both electrostatic [1] and piezoelectric [2, 3] transducers have been previously studied as promising candidates for future power electronic elements. These devices use electrostatic or piezoelectric transduction to convert energy between the input and output. We have previously demonstrated an electro-dynamic version where electrodynamic transduction (magnet/conductor interaction) is used to convert energy between two electrically isolated conductors moving in a static magnetic field [4]. The macroscale (10 $cm^3$) device, called an "electrodynamic transformer (ET)" achieved a maximum efficiency of only 6.5%. The device was applied to form a dc/ac power inverter, with only two external components: a MOSFET and a capacitor. The converter was functional, but with an efficiency of only 5.5%.

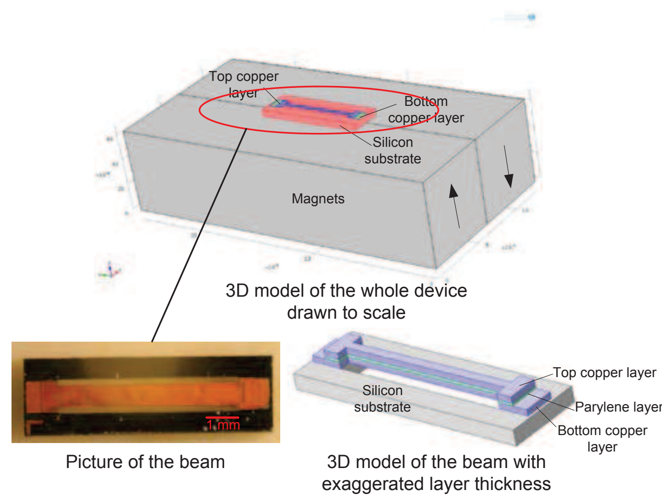


*Fig. 1: Schematic and picture of the ET.*

The follow-up study presented in this paper has two goals. The first goal is to improve the efficiency of the ET and the ET-based dc/ac converter; the second goal is to reduce the physical dimensions of the ET through microfabrication.

## DEVICE DESIGN AND FABRICATION

A schematic and picture of the microfabricated ET is shown in Fig. 1. The device (overall 7.9 mm×2.5 mm×0.5 mm) consists of a microfabricated vibrating beam structure on a silicon substrate and two NdFeB magnets (each 6.35 mm×6.35 mm×25.4 mm grade N52) arranged to create a 0.9 T in-plane magnetic field transverse to the beam. The vibrating structure is a released clamped-clamped composite beam (5700 μm×3 μm×11.5 μm) consisting two layers of copper (each 5 μm thick) isolated by a 1.5 μm layer of parylene C.

The operating principle of the device is described as follows. When an ac voltage is applied to one of the copper layers (primary conductor), the resulting current flow induces an oscillatory Lorenz force out-of-plane due to the transverse static field. The oscillatory force drives the whole beam structure to vibrate, including the other copper layer (secondary conductor). According to the Faraday's Law, an ac voltage is generated across the secondary conductor due to this motion. When an electric load is connected to the secondary conductor, electric power is transferred from the primary side to the secondary side, resembling the functionality of a transformer.

As illustrated in Fig. 2, standard microfabrication processes are used to fabricate the beam structure on a silicon substrate using 3 masks. Both copper layers are electroplated on sputtered Ti/Cu seed layers, with dimensions defined by photoresist molds. The parylene C layer is deposited via vapor deposition. A backside DRIE is used to etch through the substrate and release the beam structure.

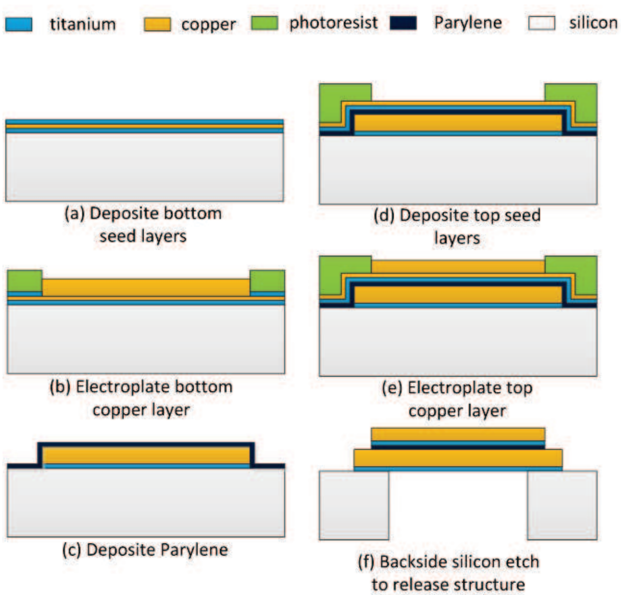


*Fig. 2: Fabrication process of the micro-ET.*

## DEVICE TESTING

The fabricated beam is mounted on the magnet assembly to test for functionality and performance. Because of the low resistance of the primary and secondary conductors (<0.5 Ω), to ensure the accuracy of the results, each bond pad is contacted by two separate test probes, requiring a total of eight probes. On each of the primary conductor's electrodes, one probe is used to source power, and the other is used to measure the actual input voltage across the conductor. On each of the secondary conductor's electrodes, one probe is used to connect to the load, while the other is used to measure the output voltage. The test setup is pictured in Fig. 3

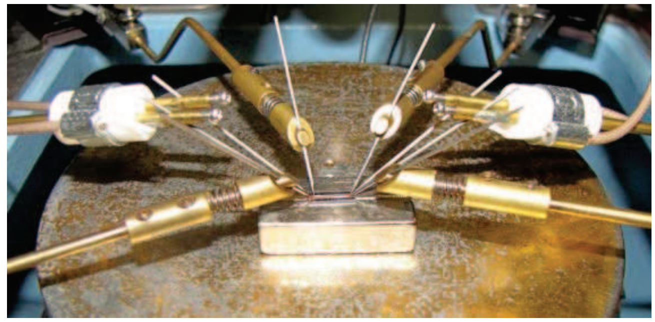

*Fig. 3: Picture of the device measurement setup.*

Before attaching any load, the open-circuit voltage gain frequency response is measured with a signal analyzer (Stanford Research Systems, SR785). The system is tested using the bottom conductor as the primary conductor. A peak voltage gain of 0.723 is obtained at 5.69 kHz, as shown in Fig. 4. According to the analytical model of the device, this peak frequency is the mechanical natural frequency of the beam.

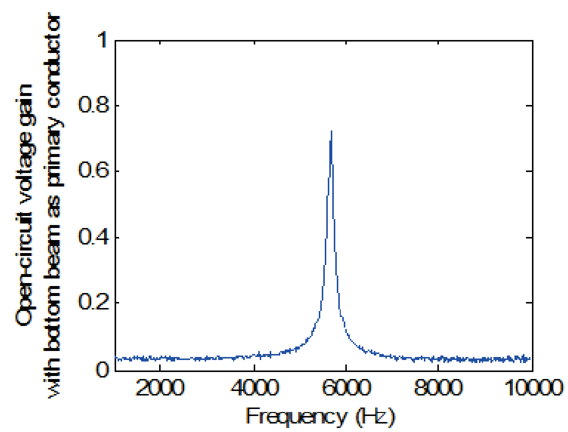


*Fig. 4: Open-circuit voltage gain frequency response.*

Different resistive loads are then connected to the secondary conductor for efficiency measurements. With each resistance value, the input power is first measured, followed by the output power and the actual load resistance. A 1 $mV_{pk}$ input voltage is supplied to the primary conductor using the SR785 signal analyzer. The low voltage level is used for this first-generation prototype to protect the device from overcurrents and/or nonlinear response. Due to the substantial measurement noise and the low signal magnitude, it is difficult to calculate the power from the time waveforms. Therefore, the power is measured via measuring the real part of the cross-spectrum of the voltage and current spectra in the swept sine mode, which theoretically gives the frequency response of the real power. The power at the mechanical natural frequency is recorded. To obtain the cross spectrum, the current is measured with a Tektronix TCP312 current probe. To measure the actual load resistance that "appears" to the secondary conductor without disturbing the setup, the ratio between the measured output voltage and output current is used to calculate the load resistance. As expected, the ratio does not change with frequency, because the load is resistive.

The measured input/output power and power efficiency is shown in Fig. 5. A maximum efficiency of 40% is obtained with 0.9 Ω load resistance. Since this is the minimum possible load resistance (achieved when the output cable was shorted), a higher efficiency may be possible if a lower load resistance were possible. Because a low input voltage is applied, the maximum output power is only 14 nW, which is again obtained when the output cable is shorted.

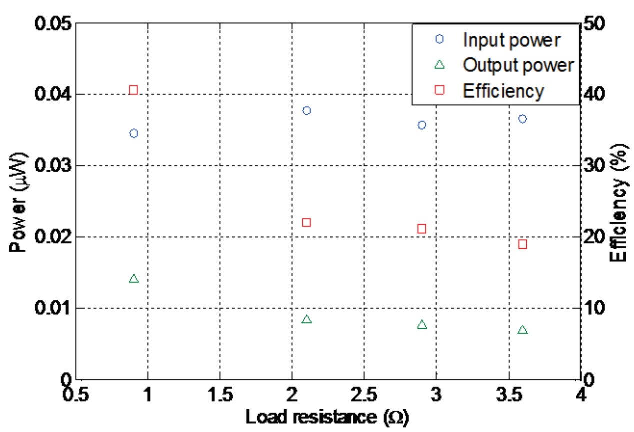


*Fig. 5: ET input/output power and efficiency vs. load resistance.*

## DC/AC INVERTER IMPLEMENTATION

As has been explained in our previous work [4], the equivalent circuit of the ET is identical to a part of the PRC-LLC resonant power converter [5]. As shown in Fig. 6, by replacing all the components in the shaded area with the ET, the part count, overall complexity, and physical dimensions of the power converter can be reduced drastically.

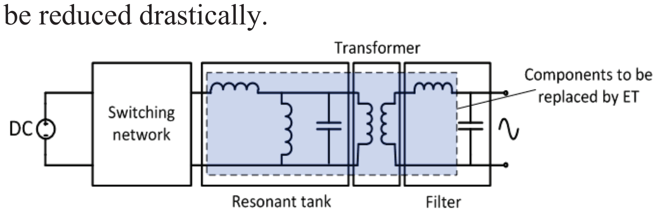


*Fig. 6: LLC-PRC resonant inverter using ET.*

Similar to our previous work, here the simplest version of the circuit is demonstrated, with only one MOSFET functioning as the switching network, and a capacitor functioning as the output waveform filter, a dc/ac inverter is demonstrated, as shown in Fig. 7.

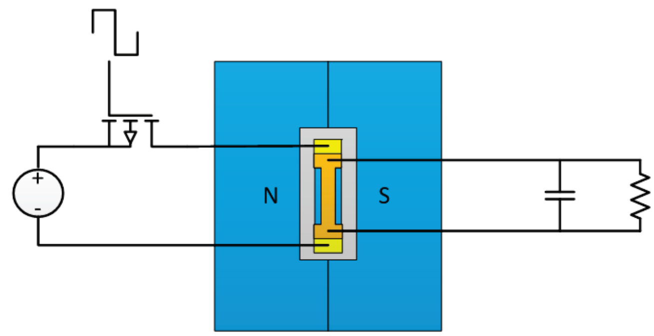


*Fig. 7: Illustration of the ET-based inverter.*

The demonstration system is configured as a resonant inverter with a 10 nF filter capacitor connected at the output. The input is provided by an isolated voltage source (Stanford Research Systems, SIM928) generating 0.01 Vdc. The power supply output is connected to a P-channel MOSFET (NDP6020P), which is controlled by a function generator (Agilent 33120A) providing a 13 Vpk square wave. The switched waveform is directly connected to the ET and filtered by the mechanical resonator, creating a close-to-sinusoidal vibration of the beam. As a result, a near-sinusoidal output voltage is generated. The voltage is slightly smoothed out by the output filter capacitor.

With the switching frequency tuned to the natural frequency of the ET, the captured waveforms are shown in Fig. 8. It can be seen that the output voltage is sinusoidal with two spikes in each cycle. The spikes are attributed to the non-zero-voltage switching of the MOSFET. The situation improves slightly as the duty ratio of the switching waveform is decreased. However, in the implementation here, zero-voltage-switching could not be achieved, possibly due to the small value of the input inductance of the ET.

The efficiency and input/output power of the ac inverter are measured on the oscilloscope with different load resistances. The power and efficiency vs. load resistance are plotted in Fig. 9. It can be seen that a maximum efficiency of 16% is obtained at the minimum achievable load resistance of 0.9 Ω. The efficiency is significantly lower than that of the ET itself. The reason probably lies in the lack of ZVS, and the performance of the MOSFET. To implement ZVS, a higher input inductance may be desired. A maximum power of 0.25 μW is delivered to the load with the 0.01 Vdc input. This is not the power capacity of the device. Unfortunately, the device was mechanically damaged before attempting to capture the power capacity with higher input power levels. Therefore, the maximum possible power density of the device is unknown.

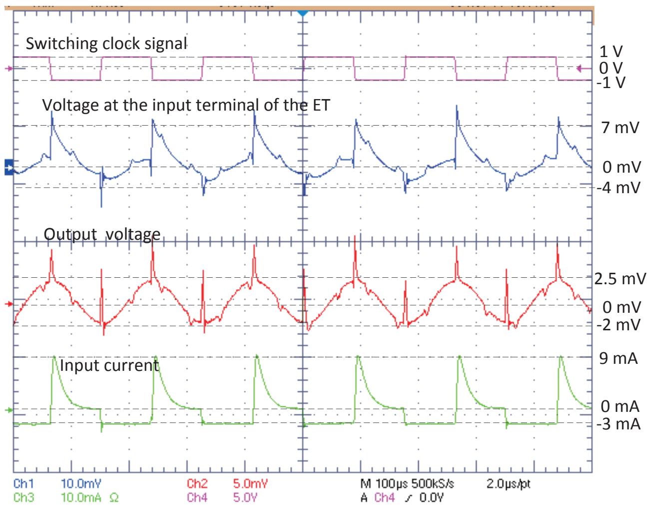

*Fig. 8: Waveforms of the resonant inverter.*

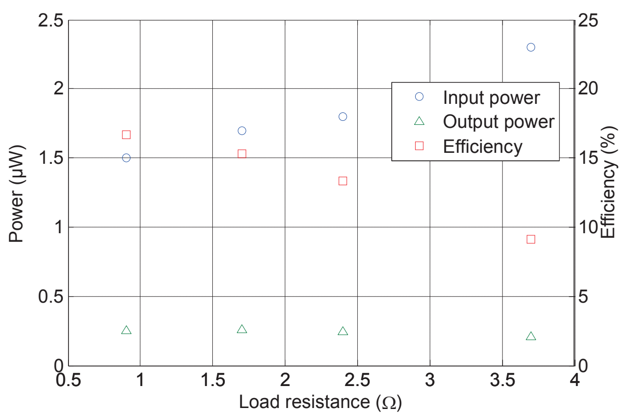

*Fig. 9: Input/output power and efficiency of the resonant inverter.*

## CONCLUSION

This work demonstrated the feasibility of microscale ET and its application in power conversion. The microfabricated device achieved a 1000x size reduction, and over 5x efficiency improvement. This achievement is due to the improved arrangement of the electrodynamic coupling configuration, where the magnetic field is perpendicular to the conductor, and both the magnetic field and the conductor are perpendicular to the direction of mechanical motion. Such configuration is believed to have superior electrodynamic coupling, which leads to higher transformer efficiency.

Further size reduction and performance improvement can be achieved by fabricating the magnet on the same substrate or a second substrate, enabling greater proximity between the magnets and the conductors. With the advance in the fabrication of micromagnets [6], it is possible to batch fabricate ETs with better performance.

Continued work is suggested to study the maximum power density of the ET and ET-based power converter.

## ACKNOWLEDGEMENT


This work was supported in part by DARPA Grant N66001-09-1-2095 and ARO Grant W911NF-09-1-0511.


## REFERENCES


[1] Noworolski J. M. and Sanders S. R. 1998 Microresonant devices for power conversion *Proc. SPIE* **3514** 260-265

[2] Yamamoto M., Sasaki Y., Ochi A., Inoue T., and Hamamura S. 2001 Step-down piezoelectric transformer for AC-DC converters *Japanese J. Appl. Phys.* **40** 3637-3642

[3] Uchino K. 2008 Piezoelectric motors and transformers *Piezoelectricity* **114** 257-277

[4] Cheng S. and Arnold D. P. 2011 A resonant DC/AC inverter using an electromechanical device *Technical Digest PowerMEMS 2011 (Seoul, Korea, 15–18 November 2011)* 355–358

[5] Liu R., Lee C. Q. and Upadhyay A. K. 1992 A multioutput LLC-type parallel resonant converter *IEEE Trans. Aerosp. Electron. Syst.* **28** 697-707

[6] Arnold D. P. and Wang N. 2009 Permanent magnets for MEMS *J. Microelectromechanical Syst.* **18** 1255-1266