2021 IEEE 20th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS) | 978-1-6654-2218-5/21/$31.00 ©2021 IEEE | DOI: 10.1109/PowerMEMS54003.2021.9658356

Wireless Power Transfer by Self-biased Magnetoelectric Laminate for Biomedical Implants

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***Abstract*—Magnetoelectric (ME) wireless power transfer (WPT) is becoming an important topic in the field of biomedical implants. Implantable ME WPT receivers have potential safety, size, and convenience advantages over alternative methods (i.e. inductive, far-field RF, and acoustic). However, for optimal performance, ME devices need some method to apply a DC bias magnetic field. To overcome the DC bias problem, this paper investigates self-biased ME laminates using the magnetization grading approach. We experimentally characterize the voltage and power performance of multi-layer self-biased ME laminates as a function of pre-magnetizing field. We demonstrate devices made of Metglas, Ni, and PZT of 0.05 cm^3 in size that can generate ~250 µW from an applied 130 µT AC field with no DC field bias. This size, power, and AC magnetic field combination makes these laminates attractive for powering biomedical implants.**

***Keywords*—Magnetoelectric, magnetization, self-biased, power, magnetization grading.**

I. INTRODUCTION

The use of magnetoelectric (ME) laminates as receivers in wireless power transmission (WPT) systems is receiving increased research attention largely due to their combination of smaller size and lower operating frequency than traditional receiving coils. The term "magnetoelectric" refers to the coupling of magnetic and electric properties of a material. In ME composites, magnetostrictive (MS) materials experience a strain due to the applied magnetic field and couple that strain to the piezoelectric material, which produces a resulting electric field.

Researchers have demonstrated WPT systems using ME laminate receivers [1], [2], [3]. However, most of these receivers need a large DC magnetic field for optimal performance. The creation of this large DC field often requires permanent magnets making the system complicated and large. If the ME laminate receiver were used to power a biomedical implant, the use of permanent magnets would cause safety issues. To overcome this problem, self-biasing approaches of ME laminates (eliminating the need for external DC biasing) has been researched. In recent years, various self-biasing approaches [4] have been investigated for ME laminates. However, most of these approaches result in devices whose performance is far below the optimal performance of externally biased devices (i.e. produce far lower voltages). Some approaches, such as exchange biasing [5], require a complicated and expensive fabrication process. Therefore, this paper suggests a technique of magnetization grading [6] to eliminate the need of DC biasing. The magnetization grading effect can be accomplished with relatively simple fabrication methods. However, for good performance, it does require that the MS materials be pre-magnetized, leaving a remanent magnetization that creates the magnetization grading effect.

In this paper we characterize the performance of self-biased ME laminates as a function of the pre-magnetizing field. Furthermore, in contrast to most prior investigations that are primarily interested in sensing performance, we focus our investigation on the power output of ME laminates rather than the open circuit voltage output.

II. THEORY

A. Magnetization grading

When two or more different magnetic materials are bonded together, an internal field is induced due to the difference in their saturation magnetizations [7]. Difference in saturation magnetizations can be achieved by choosing different MS materials with different permeability and different coercive fields. As shown in Fig.1, when two different MS materials are bonded together, an internal field (H_{int}) will be induced in the transverse direction and this field will be antiparallel to the gradient of their magnetization (∇M).

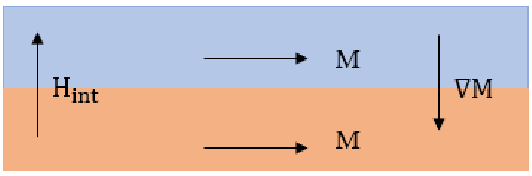

Fig. 1. Magnetization grading principal illustration. The top layer has a higher saturation magnetization. Thus, the remanent magnetization (M) will be higher for the top layer than the bottom layer resulting ∇M from top to bottom and a balancing H_{int} from bottom to top.

Therefore, according to Maxwell's equations, grading in their magnetization (M) causes a magnetostatic potential (φ) which results in an internal field (H_{int}) [6] as shown in the following equations.

$$\nabla^2\varphi(r) = \nabla . M(r) \quad (1)$$

$$H_{int}(r) = -\nabla\varphi(r) \quad (2)$$

Where, r is the position vector according to the grading direction (∇M) . The internal field, H_{int}, acts as a bias field and causes strong ME response to the ME laminate.

B. *Relation between piezomagnetic coefficient and power*

ME laminates' output power increases with the laminate piezomagnetic coefficient ($d_{33,m}$) and piezoelectric coefficient ($d_{31,p}$). Truong et al. [8] showed that power is proportional to $d_{33,m}$. The piezomagnetic coefficient $d_{33,m}$ can be defined by the slope of the magnetostriction (λ) curve ($d\lambda/dH_{DC}$). As shown in [9], the slope of the magnetostriction curve is maximum at a non-zero magnetic field (H_{DC}). Therefore, an optimum magnetic field bias needs to be applied for maximum $d_{33,m}$ and power. Magnetization graded ferromagnetic materials can act as a self-biased laminate without any pre-magnetization, but output power is generally very low. So, for magnetization graded ferromagnetic materials, pre-magnetization is necessary for optimum power output.

III. EXPERIMENTAL PROCEDURE

5-layer ME laminates have been made by using two different MS materials (annealed Nickel and Metglas) and PZT 5A.

A. *Fabrication*

5 symmetric 5-layer ME laminates (Metglas-Ni-PZT-Ni-Metglas) were fabricated by dicing and adhesion using West System 105 epoxy resin and 206 hardener. Annealed pure 99.98% Ni (Nickel-270) sheets of 250 µm thickness from Goodfellow Cambridge Limited, England, Metglas® 2605SA1 (FeSiB) foils of 23 µm thickness, and PZT-5A sheets of 500 µm thickness from Mide Technology were all diced to the dimensions shown in Table I. Metglas-Ni-PZT-Ni-Metglas laminates were adhered by epoxy and cured under a heat press at 40 °C for 5 hours. 5 similar ME laminates were made for experimental analysis. Some small differences were present in lateral dimensions due to the kerfing loss of the dicing saw and the manual dicing procedure.

TABLE I.

Materials	Length, mm	Width, mm	Thickness, mm
PZT 5A	12.36	3.81	0.5
Nickel	10.16	5	0.25
Metglas	10.16	3.81	0.023

B. *Experimental setup*

Experiments were performed by simultaneously applying an external DC bias field and an AC field, measuring the output of the ME laminates, removing the DC bias field, and then re-measuring the output of the laminates under only an AC field. In this way we characterized both the performance under an external DC bias field and the self-bias (i.e. no external applied DC bias) performance as a function of the pre-magnetizing field. Helmholtz coils were used to supply a 130 µT AC magnetic field. The DC bias field (pre-magnetizing field) was applied by using two neodymium permanent magnets. The separation distance of the magnets was varied to change the pre-magnetizing / bias field through the laminates. The experimental setup is shown in Fig. 3. Experimental steps were as follows.

- Step 1: ME laminate was placed longitudinally at the center of the Helmholtz coils.
- Step 2: 130 µT AC magnetic field and DC bias field (starting from very low bias field) by two permanent magnets were applied and output voltage readings were taken for that bias field.
- Step 3: Magnets were removed and again voltage readings of the laminate were taken in presence of AC magnetic field only (self-biasing effect is visible).
- Step 4: Distance of the two permanent magnets was decreased to apply a larger DC bias field to the laminate and steps 2 and 3 were repeated.

The above process was repeated for pre-magnetizing / bias fields from 0.1 mT to 30 mT. Step 3 shows the self-biased response due to the pre-magnetization of step 2. Due to the different magnetic properties of Metglas and Nickel, the remanent magnetization of the two materials following step 2 is different. This difference in remanent magnetization leads to an internal induced field transverse to the applied field (see Fig. 2). The magnetization-graded self-biased effect is due to this internal field. Open circuit voltage versus frequency and power at the optimal frequency versus load resistance were both recorded.

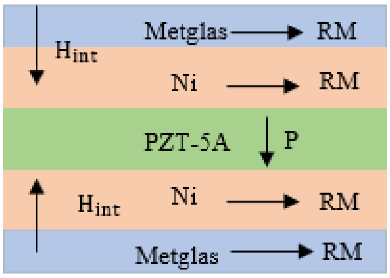

Fig. 2. Device cross-section. RM = Remanent magnetization direction, P = polarization direction

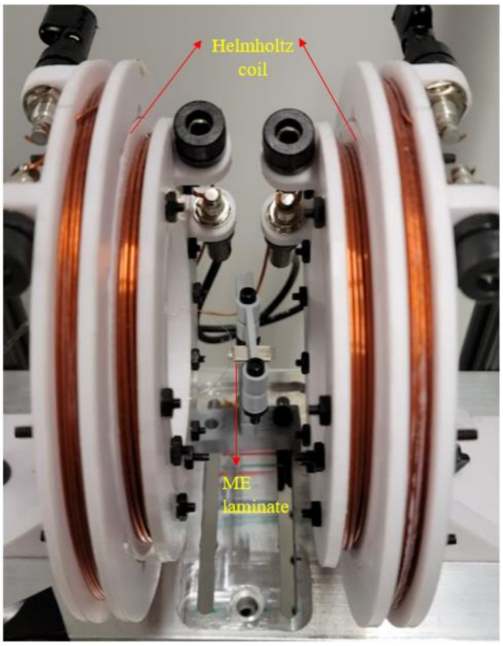

Fig. 3. Self-biased experimental setup (Step 3)

IV. RESULTS AND DISCUSSION

A. *Open circuit output voltage measurements with external DC bias field applied and after removal of bias field.*

Fig. 4 shows the open circuit voltage versus applied DC bias. Note that every curve has two visible peaks. The first peak occurs near 4 mT and could be explained by noting that the magnetostriction of Metglas will saturate above that value [10]. The second broad peak, occurring at about the maximum applied bias field of 30 mT, is indicative of the optimal bias point for Ni. After 25 mT, nickel approaches its saturation point. This basic behavior is evident in all 5 laminates (D0, D1, D2, D3, D4).

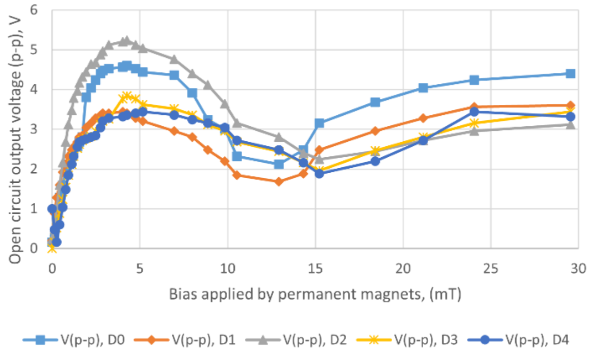

Fig. 4. Curves of open circuit output voltage of the laminates with respect to applied permanent magnet bias

Fig. 5 shows the open circuit voltages of the laminates under AC excitation after the DC bias field (i.e. pre-magnetizing field) has been removed. These data show the self-bias response of the laminates.

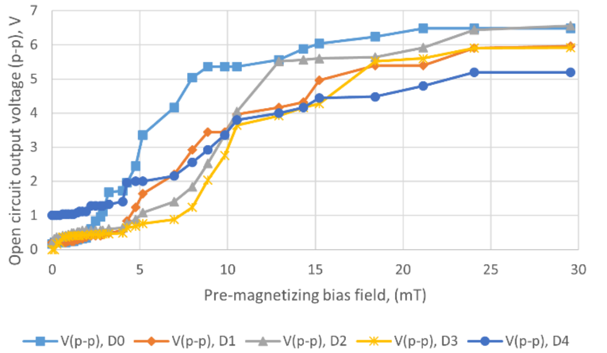

Fig. 5. Curves of the open circuit output voltage of the laminates with respect to pre-magnetizing bias field

The self-bias output voltages of the laminates increase with the increasing pre-magnetizing bias field. The output voltage increases up to about 15 mT and then stabilizes between 15 and 30 mT. Note that the self-biased performance above about 15 mT is actually higher than the output with bias applied.

B. *Self-Biased ME laminates frequency analysis*

Fig. 6 shows the frequency response of all self-biased ME laminates. The graph has been produced by applying 130 µT AC magnetic field. The resonance frequency and peak open circuit voltages for all devices are listed in Table II.

TABLE II.

Device	Resonance frequency, kHz	Open circuit voltage (peak-peak), V
D0	179.7	6.48
D1	187	5.96
D2	187.6	6.76
D3	191.1	5.96
D4	190.2	5.2

Laminate D0 is a little bit longer than the other laminates due to dicing inconsistency and hence its resonance frequency is lower than the other laminates. These differences are evident by measuring the capacitance of each device (D0 = 1.3 nF, D1 = 1.2 nF, D2 = 1.25 nF , D3 = 1.13, D4 = 1.21 nF)

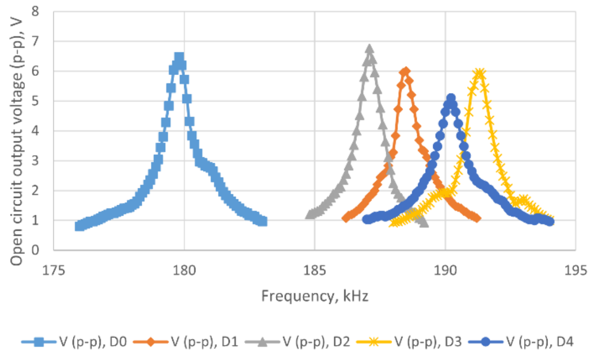

Fig. 6. Curves of the open circuit output voltage of the self-biased laminates with respect to frequency

C. *Self-biased ME laminates power analysis*

Fig. 7, shows the optimum power measurements of the laminates versus load resistance. The optimal load for all devices is near 4 kΩ.

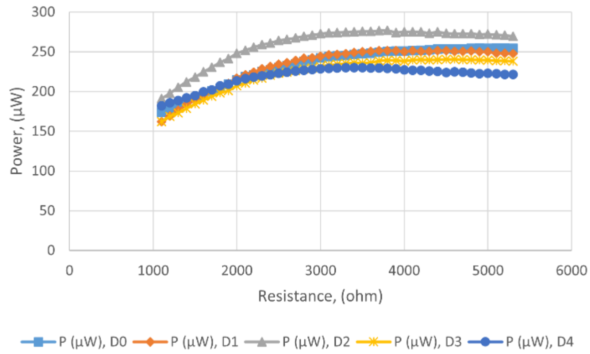

Fig. 7. Power versus load resistance curves of the self-biased laminates

The curves in Fig. 7 show that the laminates can produce power in the range of 100's of microwatts at their resonance frequency under an AC magnetic field of 130 µT, which is adequate for many biomedical implants. Laminates D0, D1, D2, D3 and D4 are able to produce 254, 251, 277, 240 and 230 µW respectively.

All five devices are nominally identical. However, there is a significant device-to-device variation as seen in Fig. 4 – 7.

Differences are likely due to dimensional variation resulting from the manual dicing and lamination process and differences in epoxy bond like thickness and quality.

Fig. 8, shows the measured optimum power output of laminate D2 versus applied AC magnetic field. As expected, power scales with the square of the applied AC magnetic field ($P \propto B^2$). Therefore, laminate D2 can produce around 1 mW at 281 µT magnetic field. According to IEEE safety standards [11], a safe field at this device resonance frequency is a little more than 100 µT for biomedical implants. From Fig. 8, it can be seen that at 100 µT, D2 is able to produce more than 160 µW, which is sufficient for many biomedical implants.

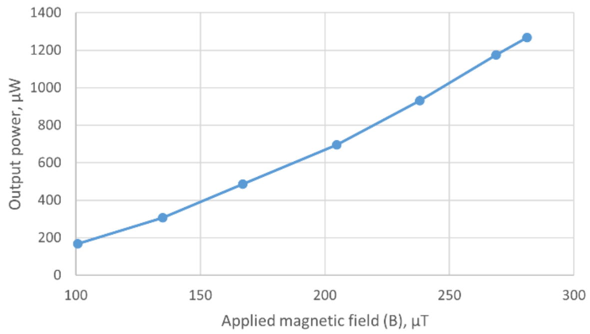

Fig. 8. Power versus applied AC magnetic field curve of self-biased laminate D2

V. Conclusion

All the laminates tested are able to produce around 250 µW power for around 130 µT AC magnetic field supply and all laminates exhibit the same characteristics. If 100 µW is accepted as a rough rule-of-thumb for the power level needed for low power wireless biomedical implants, which seems reasonable, these laminates would be able to power biomedical implants with AC fields at or below the IEEE suggested AC magnetic field restrictions. This paper suggests an easy process of pre-magnetization for making the laminates act as self-biased devices. The fabrication process is very simple and cost effective compared to other self-biased techniques. The highest pre-magnetizing field we use in this study is 30 mT. More analysis can be done for higher pre-magnetizing fields. It is apparent from our analysis that within (0 – 30) mT range, the optimum voltage output for biased condition is around 5 V (p-p) and self-biased condition is 5 -7 V (p-p). Therefore, within this range, we can say self-biased laminates perform better than biased laminates. However, the mechanism for this better performance is not understood and should be studied further.

The process described herein can be applied to any combination of MS materials such as galfenol-metglas or Terfenol-D-metglas to determine the optimum performance of self-biased ME laminates. Finally, additional analysis can be performed by changing thickness of MS and PE materials possibly enhancing performance.

Acknowledgment

This work is generously supported by the NSF Grant ECCS-1651438.

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