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Bar-shaped Magnetoelectric Gyrator

Chung Ming Leung, Xin Zhuang, Jiefang Li, and D Viehland

Department of Materials Science and Engineering, Virginia Tech, Blacksburg, VA 24060, USA.

E-mail: cmleung@vt.edu

Abstract. This paper reports a dual-resonance power transfer effect and a dual-resonance I-V conversion for a bar-shaped ME gyrator made from a hard Pb(Zr_xTi_{1-x})O₃ (PZT) ceramic bar having a transverse polarization and a Tb_{0.3}Dy_{0.7}Fe_{1.92} (Terfenol-D) magnetostrictive alloy bar having a longitudinal magnetization bonded along their cross-section areas. A bar-shaped provides several advantages to a ME gyrator; such as dual resonance frequency along its length direction, as well as half-wave and full-wave vibration modes; reduced laminate bonding area avoiding adhesive breakdown; and ease of fabrication. The reported magnetoelectric gyrator effect originates from the mechanically mediated resonance piezoelectric and magnetostrictive effects in the PZT and Terfenol-D bars, respectively. We studied the influence of the length ratio between the Terfenol-D and piezoelectric bars. A power efficiency of 69.4% was obtained at the half wavelength resonance of 21.47kHz under optimal H_{Bias} =1000 Oe and low power conditions. Under higher power drive of 8W/in³, an efficiency of 60.2% was found. This dual-resonance ME gyrator effect offers much promise in power transfer devices for power electronic applications.

1. Introduction

A gyrator is a device which transforms voltage and current, and capacitance and inductance. It was conjectured by Tellegen in 1948, as the fifth passive circuit element that had impedance conversion and lossless power transfer power features [1]. In power electronics, a gyrator was first realized by a circuit, representing capacitive-to-inductive or vice versa features. These conventional methods for gyrators were developed in the 1960s [2] based on an amplifier in an active mode which is only suitable for signal processing. Later, a different approach of a magnetoelectric (ME) laminated composite wrapped with an inductive copper coil was shown, which possessed many of features of a passive Tellegen gyrator [3]. Compared with electromagnetic and piezoelectric transformers, ME gyrators have favorable characteristics of being small and lightweight, having more uniform outputs, and variable current-tovoltage/voltage-to-current conversion gain features.

Studies of ME composite, through the product between piezomagnetic and piezoelectric effects, has resulted in small low power (passive) sensors [4-5]. A magnetic field as an input modulated with a dc magnetic field induces a strain in a magnetostrictive layer, which is transferred to the piezoelectric layer that provides a voltage output. The composite layers are laminated and bonded together (e.g. epoxy adhesive, co-firing, etc.) into structures of various layer configurations [6-8]. Although trilayer ME structures demonstrated, giant ME coupling effects at both non-resonance and resonance frequency ranges, due to strain transfer between layers, this strain mechanism is strongly dependently on bonding methods/materials, that may generate strain lag or mechanical loss [9-10]. In practice, there is no ideal adhesive interface for strain transfer in ME composites that can provide perfect bonding; therefore, a

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better solution is to reconfigure the structure from trilayers to bar-shaped. Compared with tri-layer structures, the drawback of a bar-shaped ME composite is that it will only provide a high ME response near resonance, and a much lower response at non-resonance conditions.

In this paper, we have developed a bar-shaped ME gyrator by combining magnetostrictive and piezoelectric bars. It consisted of Terfenol-D bars with the magnetization in the longitudinal direction and PZT bars with the polarization direction along their thickness direction of various lengths. Due to the bar-shaped structure, the proposed gyrator has two interesting resonance power transfer peaks, including a first fundamental (half-wave) and a second resonance (full-wave). By optimizing the length between the Terfenol-D and hard PZT bars, a maximum power efficiency (η) and *I-V* conversion ratio of 69.4% and 5250V/A, respectively, were obtained at the first fundamental resonance. A low reduction of power efficiency was found with increasing power drive density to 8W/in³.

2. Materials and Experiments

Figure 1 shows a schematic diagram of our bar-shaped ME gyrator. The ME gyrator had a lengthmagnetized magnetostrictive layer and a thickness-polarized piezoelectric one. Terfenol-D and hard PZT bars were selected as the magnetostrictive and piezoelectric layers, respectively. The dimensions of the Terfenol-D bar were fixed at $18 \text{mm} (l_m) \times 6 \text{mm} (w_m) \times 2 \text{mm} (t_p)$, while the PZT piezoelectric bar was $64 \text{mm} (t_p) \times 6 \text{mm} (w_p) \times 2.2 \text{ mm} (t_p)$. These two bars were then bonded along their cross-sectional areas $(w \times t)$ using the non-conductive epoxy adhesive for 6 hours at a temperature of 60° C. After full curing of the epoxy, the ME composite was put into the copper coil to form a ME gyrator. The ME laminate was wrapped by a 0.1mm diameter copper wire with 1000 turns and a cross-section area of 200mm². Detailed fabrication procedures can be found from previous articles [11]. To study the length effect of piezoelectric bars in the ME gyrator, the hard PZT bars were cut by a dicing saw from the original length of 64 mm to 54, 45, 36, 27, 18, 9 mm after each characterization measurement.



Figure 1. Schematic diagram of our bar-shaped ME gyrator.

The working principle of our ME gyrators is based on the product of the electromagnetic effect in the copper coil, the direct magnetoelastic effect in the Terfenol-D bar, and the direct elastoelectric effect in the PZT bar. An ac magnetic field (H_{ac}) was excited by the input electric current (I_{in}) in a copper coil (inductive port) which was wrapped around the Terfenol-D. This ac magnetic field induced a magnetostrictive strain in the Terfenol-D bar which was transferred to the PZT bar, via the bonding interface. As a result, an induced voltage (V_{out}) was generated from the piezoelectric bar (capacitive port) across a resistance load (R_L). To characterize the bar-shaped ME gyrator, two important features were tested: power efficiency and *I-V* conversion ratio.

The properties of the ME gyrators were measured using an in-house measurement system under freefree boundary condition [12]. The magnetic field bias was applied parallel to the ME laminate, which was supplied by a water-cool U-shaped electromagnet controlled by a dc power amplifier. The copper coil was driven by a signal generator via an ac power amplifier. A voltage amplifier was used to provide a high impedance input condition for the measurements. The gyrator was also connected to a dynamic signal analyzer to collect data in a swept-mode. The power efficiency of the bar-shaped ME gyrator was defined as follows: the input power (P_{in}) was calculated as the real portion of the product of I_{in} and V_{in} , and the output power (P_{out}) was calculated by dividing the output voltage (V_{out}) squared by the resistance load (R_L) connected to the piezoelectric bar. Finally, the power efficiency was defined by dividing the output power by the input power ($\eta=P_{out}/P_{in}$). The *I-V* conversion ratio (V/I) was calculated by dividing the output voltage (V_{out}) from the piezoelectric bar by the input current (I_{in}) from the copper coil.

3. Results and Discussion

Figure 2 shows the frequency dependence of the power efficiency (η) for piezoelectric bars of various l_p . Two sharp power efficiency peaks, corresponding to the half-wavelength (fundamental) and full-wavelength (second) longitudinal resonances, were observed for all values of l_p of the piezoelectric bar. It is clearly shown that the power efficiency was strongly dependent on the length ratio between the Terfenol-D and piezoelectric bars. The maximum value of η was found to be 69.4% at the first resonance frequency of 21.47 kHz, and η =34.5% at the second resonance of 42.2 kHz with l_p =54mm.





Figure 2. Measured power efficiencies (η) spectra of the bar-shaped gyrators with piezoelectric bars of various lengths. The insert is the optimal resistance load as a function of the length of piezoelectric bars.

Figure 3. Measured *I*-*V* conversion ratio (V/I) spectra of the ME gyrators with piezoelectric bars of various lengths. The insert is the maximum *I*-*V* conversion ratio, from which the spectra were extracted.

The power efficiency decreased with increasing l_p for the first resonance (half-wave), and increased with increasing l_p for the second resonance (full-wave) reaching a maximum value of 44.9% at 65.77kHz for $l_p=27$ mm. In addition, the resonance frequency was shifted to the higher values with decrease the length of the piezoelectric bar. To give physical insight into the optimal resistance load (R_L) effect, the l_p dependence of the optimal resistance load (R_L) of the ME gyrator was measured, given in the insert. The optimal resistance load decreased as the length of the piezoelectric bars was increased, agreeing well with the maximum power transfer ($R_L=1/\omega C_0$) where C_0 is the clamped capacitance of the piezoelectric bar [13]. Although C_0 was decreased with reduced length of the piezoelectric bar, the optimal resonance frequency was increased more significate than the decreasing C_0 . Therefore, in order to obtain a higher output power, the dimension of the ME gyrator needs to be increased.

Figure 3 shows the *I-V* conversion ratio as a function of frequency, taken at a constant I_{in} of 1 mA for various l_p of the piezoelectric bars. The insert of Fig.3 is the maximum *I-V* conversion ratio, which was extracted from the *I-V* conversion frequency spectrum. A maximum *I-V* conversion of ~5250V/A was found for l_p =54mm at a frequency of 21.7kHz. This agreed well with the finding of a maximum in the power efficiency. In addition, a maximum *I-V* conversion for the second resonance was found at 63 kHz for l_p =27mm. A slight shift of the resonance between maximum power efficiency and maximum *I*-

V conversion and these results were also found for the trilayer ME gyrator [13]. An improved I-V conversion ratio could be obtained if the number of turns of the copper coil was increased.

Next, the effective magneto-mechanical coupling $(k_{m,eff})$ and quality (Q) factors were measured at the inductive port, also the effective electromechanical coupling $(k_{p,eff})$ and quality factors were measured at the capacitive port, respectively, as shown in Figs. 4(a) and 4(b). The values of $k_{m,eff}$ and Qwas about 0.5 and 8 (measure) for the Terfenol-D, and those of $k_{p,eff}$ and Q were 0.35 and 500 (from manufacturer) for hard PZT. It was found that $k_{m,eff}$ decreased and $k_{p,eff}$ increased when l_p of the piezoelectric bar was increased, while the Q factors measured at both inductive and capacitive ports increased with increasing l_p . These property changes dictate the need for the balancing the length ratios between the Terfenol-D and PZT bars. Since the Terfenol-D bar had a higher coupling factor enhancing the effective coupling at inductive port, the ME gyrator could have a shorter l_p for the piezoelectric bar. On the other hand, Q in the piezoelectric bars was found to enhance the effective Q of the ME gyrator with increasing l_p .





Figure 5. The measured power efficiency of a ME gyrator having a piezoelectric bar with a length of 54 mm.

Figure 4. (a) $k_{\text{eff,m}}$ and Q factors of the ME gyrators with piezoelectric bars of various length. (b) $k_{\text{eff,p}}$ and Q factors of the ME gyrators with piezoelectric bars of various length.

Figure 5 shows the power efficiency of the bar-shaped ME gyrator for $l_p=54$ mm as a function of the power density, under an optimal $H_{\text{Bias}}=1000$ Oe and $R_{\text{L}}=4.3\text{k}\Omega$. Although the power efficiency decreased with increasing power density, the value still remained higher than 60%. This is because the bar-shaped ME gyrator can reduce the interface loss in the bonding adhesive. It is clear that the reduction of the power efficiency in bar-shaped gyrators of Terfenol-D/PZT is due to a power loss of mechanical vibrations, in addition to heat loss from copper coil.

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4. Summary

In summary, bar-shaped magnetoelectric gyrators with piezoelectric bars of various l_p of 9, 18, 27, 36, 45, 54, 64 mm have been studied. The ME gyrators were fabricated using hard PZT ceramic bars for the piezoelectric phase and Terfenol-D alloy bars for the magnetostrictive one. The maximum power efficiency and *I-V* conversion were found to be ~69.4% and 5250V/A, respectively at the fundamental resonance under a resistance load (R_L) of 4.3k Ω (power efficiency measurement) and an open condition (*I-V* conversion measurement). This ME gyrator has the potential for use in high power solid-state ME converters due to the reduction of bonded area.

Acknowledgments

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