Influence of shape on power conversion efficiency of Ni-Zn ferrite/piezoelectric magnetoelectric gyrator

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Abstract. Reducing the demagnetization effects via shape optimization in tri-layer magnetoelectric (ME) composite is an effective way to improve its power transfer conditions. To accomplish this goal, enhanced dynamic piezomagnetic coefficient of Ni₀.7Zn₀.3Tb₀.02Fe₁.98O₄ ferrite, the tri-layer Ni₀.7Zn₀.3Tb₀.02Fe₁.98O₄/PZT/ Ni₀.7Zn₀.3Tb₀.02Fe₁.98O₄ ME composites under different L/W ratios with coil wound around for gyrator fabrication were systematically characterized. Measurements of resonance ME responses were carried out for samples with the varying L/W ratio, the weak demagnetization field occurs at the sample with highest L/W ratio, yielding a stronger ME coupling. Experiment results of PE characterizations demonstrated that maximum of 91.3% was achieved under optimum bias and EMR driving in sample with higher L/W = 17.5. Therefore, the higher PE is originated from strong dynamic magneto-mechanical response under the shape optimizations. These findings provide the possibility of ME gyrator in high energy conversion power electronics devices.

1. Introduction

As a hypothetical component, gyrator featured passive, linear and lossless properties, was initially conjectured by Tellegen in 1948. Unlike four fundamental electric components of resistor, inductor, capacitor and transformer, gyrator was reckoned as the fifth missing component and can make a capacitive circuit behavior inductively or vice versa with direct V-I/I-V conversions. In the last decades, magnetoelectric (ME) composites exhibiting ferroelectricity and ferromagnetism simultaneously, have drawn much attentions due to the capability between electric and magnetic energies exchange[1], and ME composites can be designed over a wide range of compact and multifunctional electronic devices[2-4]. Therefore, this emerging research field provides a great possibility to fulfill the requirements of the gyration characteristics and the feasibility of gyrators. From the earliest years of ME gyrators development, the investigation of ME gyrators was pioneered by Zhai et al. in 2006, and solid evidence was provided by characterizing the ME composite to demonstrate the feasibility of gyrators existing as a non- reciprocal electric element, and the Tellegen’s previous conjecture has been proven to be achievable by using the composite[5]. In 2009, Zhai et al. performed comparison studies of gyration characteristics in ME composites at their electromechanical (EMR) resonances with three distinct ferromagnetic materials, and an equivalent circuit was introduced to evaluate their capacitance to inductance capabilities[6]. Since 2016, focused efforts are essential on improving the power conversion efficiency (PE), and the higher PE that is related to strong ME couplings will continue to depend on
efficient magneto-mechanical-electric transfer[7]. In this regard, techniques including structural/parametric optimizations, mechanical loss decreases were employed to fulfill this requirement [8-11]. Very recently in 2019, Zhang et al. reported an efficient ME gytor composed of nickel-iron-based constant elasticity alloy with high quality factors and piezoelectric ceramics, low mechanical loss can be guaranteed in the process of magneto-mechanical-electric conversion so that the maximum PE reached as high as 88.5% under extremely low input power density of 3.31μW/cm^2[12]. Zhuang et al. introduced an equivalent input loss factor into Mason’s model to describe the power conversion and loss process in Metglas/hard-PZT ME gyrators with higher achievable PE of 92% [13]. The highest PE of 95% was achieved in nanocrystalline Metglas/Hard Mn-doped PMN-PT ME composite at R_L=5kΩ reported so far [14]. The ever-increasing demand for device miniaturization in ME gytor has propelled the exploration of methodologies, in 2011 Cui et al. studied the size induced demagnetization effect on ME couplings and they concluded that a thin and long ME composite will exhibit stronger ME couplings due to its low demagnetization field[15]. Although influences of size demagnetization effect on ME couplings have been reported to further improve ME interactions, studies on the induced PE involving energy transfers in this field remain fairly limited. To reduce the demagnetization effects, an attempt to increase the length-width ratio (L/W) in ferrite/Metglas/PZT ME composite was done by Leung et al. in 2018. The increased L/W facilitates the enhancement of the magnetic flux concentration and the reduction of the required bias, eventually the maximum self-biased PE of 72% can be achieved under L/W=18.7[16]. In addition, shape optimization of ME samples works for the further improvement of ME couplings due to the enhancement of effective magnetic field. Nevertheless, the mechanism will suffice to illustrate how the demagnetization effects can influence the dynamic magneto-mechanical conversion and eventual power conversion is still not clear, and no work has been reported so far.

In this study, a variety of ME gyrators composed of terbium-doped nickel ferrite and piezoelectric ceramic under varying L/W ratios were fabricated with coil around and systematically characterized. Measurements of dynamic piezomagnetic coefficient, resonance ME response and PE were performed. It is expected that the ME gytor with higher L/W ratio thus allowing for minimum demagnetization field, anticipating an enhancement in dynamic magneto-mechanical response as well as the power conversion efficiency. These studies have promoted the efficient energy transmission of the ME gytor and the miniaturization development of devices.

2. Experiment
Tri-layer samples of ferrite/PZT/ferrite were synthesized using standard solid state sintering techniques. The rare earth ions of Tb^{2+} improve magnetocrystalline anisotropy and magnetostriction through magnetoelastic interactions with its ligand coordination. To this end, the ferrite power necessary was prepared by commercially available power of NiO, ZnO, Fe_{2}O_{3} and Tb_{2}O_{3} in compliance with strict mole ratio of Ni_{0.7}Zn_{0.3}Tb_{0.02}Fe_{1.98}O_{4}, an approximately 15h ball milling was performed to grand the mixture to submicron size, followed by pre-sintering and final-sintering programs with heating/cooling rate of 2ºC/min in a muffle furnace. To obtain samples with different L/W ratios, sintered ferrite blocks were cut into thin pieces with the same thickness of 0.5mm and desired sizes. The lead zirconate titanate (PZT) slabs were chosen as piezoelectric materials due to the high quality factor and relative low impedance, and then the ME gytor was fabricated with the PZT slab bonded to the ferrite platelets using epoxy resin adhesive with a 320-turn coil wound around it. For the ME characterizations, the sample was centered in a solenoid powered by an AC current source (Keithley Model 6221), and the induced ME voltage was captured by a lock-in amplifier (Ametek Model SR7280). Magnetic bias field was generated by an electromagnet (Eastchanging Technologies Model EM3) powered by a bipolar DC current source. For PE characterization, input power (P_i) of ME gytor was provided by a function generator (Tektronix Model AFG3021B), and a load resistor of 1Ω was serially connected into the input loop for input current (I_i) acquisition. A variable load resistor (R_L) was connected directly to the PZT slab for matching maximum output power (P_o). Dynamic piezomagnetic properties were measured by a laser Doppler vibrometer (Polytec Model OFV-5000/50S5).
3. Results and discussion
The dynamic piezomagnetic coefficient \(d_{33m}\) of the ferrite platelet represents the capability of instantaneous magneto-mechanical conversion in ferrite samples. To focus on the influences of demagnetization effects on dynamic piezomagnetic response, dimensions of ferrite samples were tailored to different \(L/W\) ratios for the purpose of weakening the shape demagnetization effects. Figure 1 illustrates the in-plane piezomagnetic spectrum in the vicinity of resonance frequency for five ferrite platelets with different \(L/W\) ratios, results show that the maximum \(d_{33m}\) of 49.3ppm/Oe occurring at sample with highest \(L/W=17.5\) while the minimum of 28.6ppm/Oe occurring at the one with lowest \(L/W=4\). We also found that the appearing resonance frequency is mainly determined by length, so that the shorter sample has higher resonance frequency. The most important point to be gained from this figure is how the size optimization facilitates the improvement of dynamic piezomagnetic response, and demagnetization effects will be responsible for this improvement. Since demagnetization factor \(N_D\) is mainly determined by sample’s sizes, longer and narrower samples will result in a lower \(N_D\) as well as weak demagnetization field.

![Fig.1 In-plane dynamic piezomagnetic spectrum in the frequency range of 70kHz-145kHz for the samples with different \(L/W\) ratio.](image)

Magnetoelectric composite serves as key transducing element in the gyrator due to its strong intrinsic magneto-mechanical-electric couplings. Therefore, the measurements of the frequency dependence of MEVC were done to describe the resonance behavior for longitudinal-transverse mode, and the representative MEVC vs \(f\) profile was illustrated in Fig. 2 for a variety of ME samples with different \(L/W\) ratios. The magnitude of MEVC and the appearing EMR frequency are in coincidence with the data in \(d_{33m}\) vs \(f\) profile, namely that Fig.2 shows a similar variation in the profile of piezomagnetic response. The only difference is the EMR frequency in MEVC vs \(f\) profile is much lower than that in MEVC vs \(f\) profile, which is attributed to the additional thickness with PZT laminated in ME samples. As the \(L/W\) ratio is changed from 4, the corresponding peak MEVC exhibits an approximately linear increase to a maximum of 458V/cm Oe at \(L/W=17.5\). We infer from the results that enhancement in ME coupling with lower \(L/W\) ratio is mainly related to a reduction in demagnetization field, resulting in high effective magnetic field and, therefore, an efficient magneto-mechanical conversion in ferrites.
Next, the dependence of the PE of the ME gyrators with different L/W on the load resistance is characterized. To accomplish this goal, PE vs R profile was measured under EMR and optimum bias with a variable load resistance range of 100Ω-400kΩ for three samples. As the load resistance is increased from 100Ω, from Fig.3 we know that PE shows a sharp increase and then reaches its maximum at their optimum load resistance for samples with various L/W ratios. The experimental results show the maximum PE of 91.3% at R_L=25.6 kΩ still occurred at the sample with highest L/W ratio. We infer from the results that the influences of demagnetization effects dominates the improvement of PE rather than the capacitance, therefore, solid evidence was provided to verify that the actuating port of ME gyrator largely restricts the PE improvement. Moreover, the maximum PE vs L/W profile can essentially track d_{33m} vs L/W profile, lower demagnetization effects induced strong dynamic magneto-mechanical coefficient will facilities the enhancement of magneto-mechanical-electric conversion in ME gyrators.

4. Conclusions
In summary, influences of demagnetization effects on energy transfer efficiency for ME gyrators with a variety of L/W ratios were systematically investigated. The terbium-doped Ni_{0.7}Zn_{0.3}Tb_{0.02}Fe_{1.98}O_{4} were synthesized and their dynamic piezomagnetic coefficients were characterized under different L/W with strongest magneto-mechanical responses for the following studies. Subsequently, tri-layer ME samples of Ni_{0.7}Zn_{0.3}Tb_{0.02}Fe_{1.98}O_{4}/PZT/Ni_{0.7}Zn_{0.3}Tb_{0.02}Fe_{1.98}O_{4} with its L/W ratio varied from 4 to 17.5 were fabricated, the measurements resonance MEVC and the PE were carried out. Results show that the weak demagnetization field caused by the high L/W ratio of the ME gyrator improves the magneto-mechanical conversion, hence the PE of 91.3% can be obtained under higher L/W ratio of 17.5 with optimum bias and EMR driving. These findings provide great potentials of using the shape-optimized gyrators for...
miniaturization realization in application of power electronics, converters and isolators.

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