A CHIP-SCALE RF MEMS GYRATOR VIA HYBRIDIZING LORENTZ-FORCE AND PIEZOELECTRIC TRANSDUCTION MECHANISMS

Novelty / Progress Claim(s)

This paper presents the design and experimental results of the first chip-scale RF MEMS gyrator based on hybridizing Lorentz-Force and Piezoelectric transduction. The MEMS gyrator has a non-reciprocal phase response and can be used as the building blocks for synthesizing complex non-reciprocal networks. The equivalent circuit and measured performance of a fabricated MEMS gyrator are presented, showing the anticipated 180° phase difference and marking the first time non-reciprocity is attained with a fully passive chip-scale mechanical device. Various challenges in attaining larger coupling and low insertion loss for the designed devices will be discussed.

Background / State of the Art

Radio frequency (RF) non-reciprocal networks are key enablers for full-duplex radios that can simultaneously transmit and receive over the same bandwidth. However, conventional nonreciprocal devices are typically bulky and difficult to integrate at chip-scale, as their sizes are comparable to large EM wavelengths. To drastically reduce the size of non-reciprocal devices while maintaining competitive performance, acoustic waves can be leveraged because its wavelength is four to five orders of magnitude smaller than their EM counterparts [2]. To implement such a principle, an electromechanical gyrator that harnesses the voltage-current gyration in a resonant magneto-electric transducer has been designed. The magneto-electric transduction in this work is achieved by utilizing Lorentz-force and piezoelectric transductions in tandem in a single structure, which has never been exploited for chip-scale nonreciprocity before.

Description of the New Method or System

As shown in Fig. 1, our device is essentially a laterally vibrating piezoelectric resonator (LVR) mechanically coupled with an inductively transduced resonator. In operation, the two-port gyrator can be either piezoelectrically driven via the interdigitated electrodes or magnetically excited via the coil by Lorentz. In the forward path, the applied AC voltage across the coil (Port 1) would generate a magnetic force under the external magnetic field (i.e., Lorentz force), exciting the AlN structure into a higher order extension mode vibration. As the strain produced by the Lorentz force couples into the piezoelectric material, it converts to a voltage across Port 2 via piezoelectric transduction (90° lagging the voltage across the coil loop). In the backward path, the voltage applied to Port 2 piezoelectrically excites the structure to vibration, the energy of which is converted to a current in the coil via Faraday's law of induction, yielding a voltage (90° leading the voltage across Port 2). Consequently, the nonreciprocal phase difference between the forward and backward paths is 180°. In comparison to other EM gyrators, our design enables a drastic reduction in the gyrator size, while allowing the coupling coefficient to be independently controlled through an external magnetic field bias.

Experimental Results

The device was fabricated with a four-mask process, as shown in Fig. 2. The device consists of 100 nm Pt as the bottom electrode, 1 µm of AlN piezoelectric layer, and 200 nm Al as the top electrode for the piezo port as well as the coil loop for the inductive port. Fig. 3 shows the SEM image of a fabricated gyrator device with a dimension of 130 µm by 200 µm and Fig. 4 shows the measurement setup. The resonant frequency of such a gyrator is determined by the width of AlN plate and electrode pitch as well as properly designed coil position for maximum displacement. The equivalent circuit and simulation results are shown in Fig. 5 while the characterized data are plotted in Fig. 6. Thanks to the enhancement of nonreciprocity at resonance, the fabricated device exhibits gyration near 261.3 MHz under a magnetic field of 2800 Oe, with nearly the same transmission magnitude and a 180° difference in phase. Simulation predicts that the gyration efficiency can be improved by further increasing the external magnetic field.

Word count: 599

References

[1] B.D.H. Tellegen, *Philips Res. Rept.*, 3(1948), pp. 81–101.
[2] T. Wada et al., *Proc. IEEE MTT-S Int. Microwave Symp. 2014*, pp. 1–3.

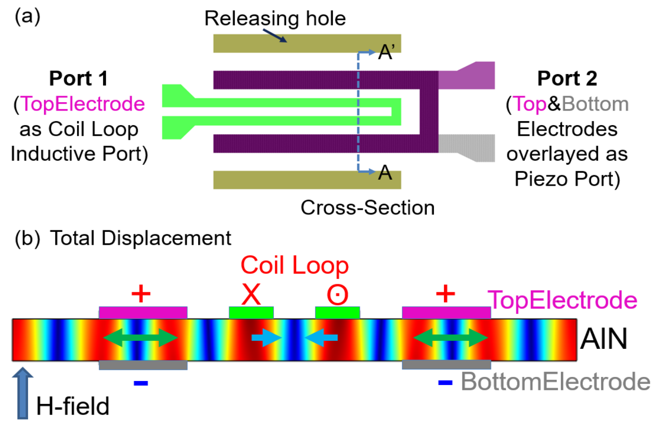


Figure 1: (a) Top view of the proposed RF MEMS Gyrator. (b) Simulated cross-sectional view (A-A') of the AlN gyrator displacement mode shape at resonance.

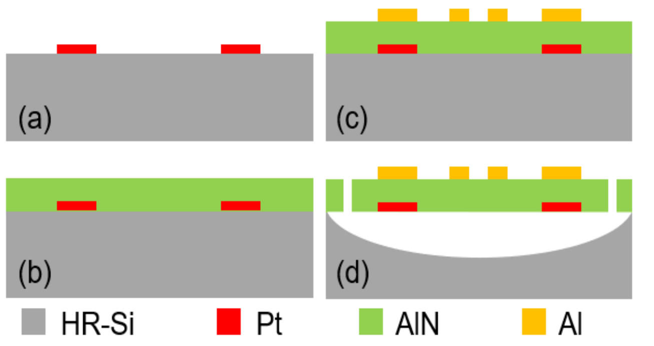


Figure 2: Fabrication process: (a) 100 nm Pt is deposited on a high-resistive Si substrate (HR-Si) using lift-off process; (b)1 μm AlN is sputtered and the via is patterned using wet-etching; (c)200 nm Al is patterned using a lift-off process; (d) AlN layer is patterned using an ICP etcher and the gyrator is released by XeF_2 etching.

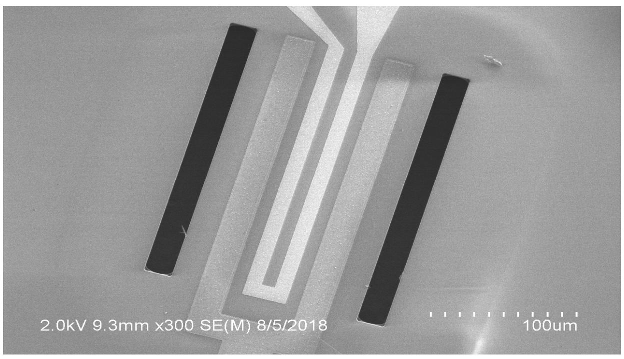


Figure 3: SEM of a fabricated gyrator device.

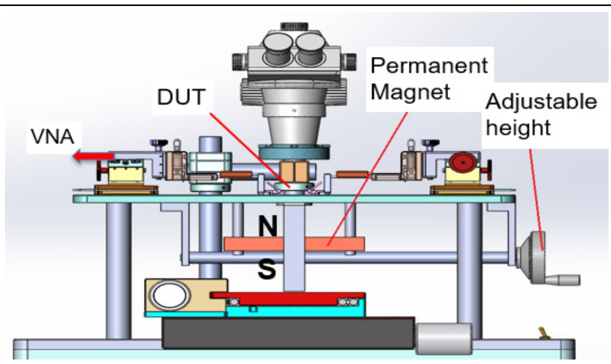
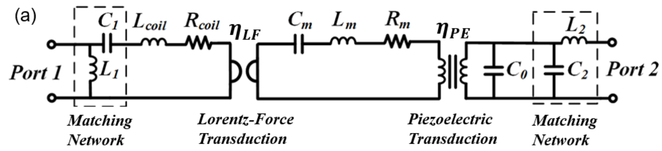


Figure 4: Measurement setup with adjustable permanent magnet height for varying the external magnetic field bias.



$$\eta_{LF} = \frac{F_{LF}}{I_{Coil}} = BL \qquad \eta_{PE} = \frac{F_{PE}}{V_{PE}} = 2e_{31}L$$

C_m	L_m	R_m	L_{coil}	R_{coil}	C_0
54.12 nF	6.86 pH	1.04e-5 Ω	0.6 nH	15.3 Ω	0.9 pF
B	L	e_{31}		η_{LF}	η_{PE}
0.28 T	200 μm	0.6 C/m²		5.6e-5	2.4e-4

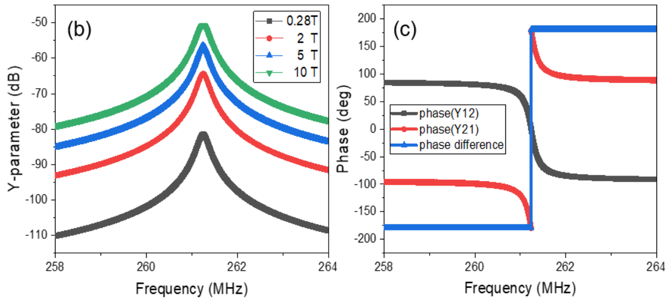


Figure 5: (a) Equivalent circuit model for the MEMS gyrator: L_{coil} and R_{coil} represent the inductance and resistance of the top coil; C_m, L_m, and R_m are the equivalent spring, mass, and damper in the mechanical domain; the ideal gyrator model captures the Lorentz-Force transduction with a coupling coefficient of η_{LF}, while the transformer captures the piezoelectric transduction with a coupling coefficient of η_{PE}; C_0 is the static capacitance of the piezoelectric film; (b) Simulated Y-parameters in magnitude dB at different magnetic field biases of 0.28 T, 2 T, 5 T and 10 T; (c) Simulated phases of Y_{12}, Y_{21} and phase difference at the magnetic field bias of 0.28 T.

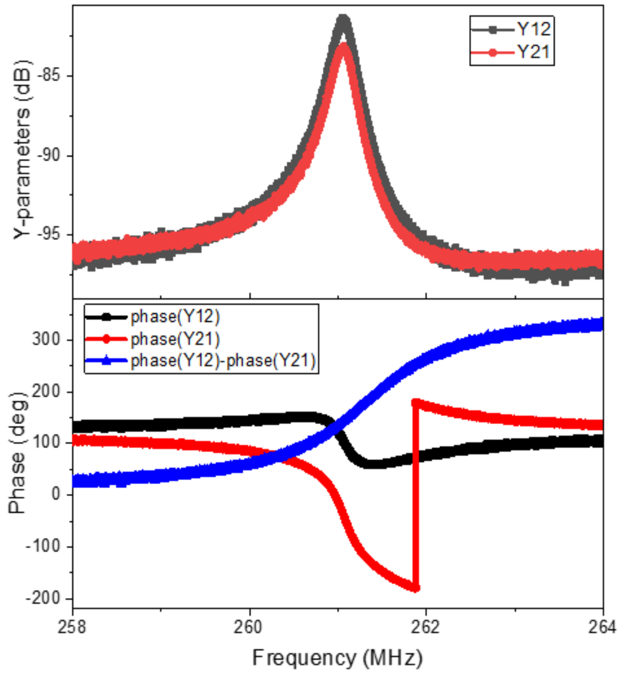


Figure 6: Characterized MEMS gyrator Y-parameter in (a) magnitude (dB) and (b) phases (degree) at the maximum applied external magnetic field bias of 0.28 T (2800 Oe); the nonreciprocal 180° phase difference occurs at approximately 261.3 MHz due to the enhanced Lorentz-Force gyroscopic transduction mechanism around the resonant frequency.