Lamb Wave Resonator Loaded Non-reciprocal RF Devices

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***Abstract*—In this paper we explore parametric amplification on the Lamb wave acoustic platform for the purpose of developing nonlinear and non-reciprocal devices. The strength of the acoustic wave platform over the electromagnetic platform is its low loss and short wavelength at radio frequency which enables devices with a small footprint and high quality factor. Compared to surface acoustic waves, Lamb waves exhibit much higher phase velocity which support higher frequency operation with fabrication tolerance. To realize parametric amplification, the intrinsic nonlinear stiffness of aluminum nitride is used to couple acoustic waves at different frequencies. Novel Lamb wave resonator structures and non-reciprocal devices implementation have been proven in theory and simulation. Experiment of Lamb wave transducers demonstrates parametric effects and proves nonlinearity in AlN thin films.**

***Keywords*—Lamb wave resonator, non-reciprocal devices, nonlinear stiffness, parametric amplification.**

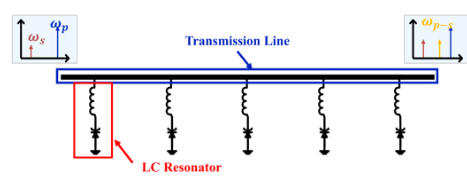
I. Introduction

In response of rapid development of wireless communication, high performance and small form factor RF front-end modules are required. Non-reciprocal devices are key components in the front-end module because they separate signals based on traveling direction. Traditional non-reciprocal devices reply on ferrite magnetic materials that are bulky and incompatible with standard mobile manufacturing process. To solve this issue, parametric amplification based non-reciprocal devices have received a lot of attention recently because it has an intrinsic low loss and low noise property. Parametric amplification is achieved by varying the properties of reactance-based components in space and time. One way to realize parametric amplification and non-reciprocity is to use a time-varying transmission line (TVTL) [1,2]. This unique concept allows separation of waves which travel in different directions. When a traveling pump wave ω_m is injected in a transmission line along with the signal wave ω_s, signals propagating in the same direction as the pump wave mix with the pump wave, generating two sidebands at ω_{m-s} and ω_{m+s}. However, signal waves traveling in the opposite direction of the pump wave do not generate the two side bands. Consequently, the difference in the propagating direction of the signals is translated into the difference in signal frequencies. These differences produce signal separation and realize non-reciprocity. MMIC implementation of TVTL has demonstrated a maximum conversion gain of 2.4 dB over the desired frequency range of 0.5GHz to 2.5GHz [3]. However, the loss and low quality factor associated with microwave transmission lines degrade the noise performance of TVTL.

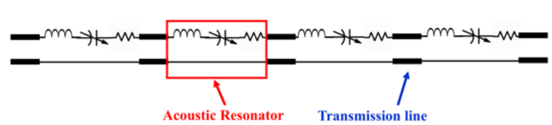
Acoustic wave devices have been widely studied for filters, diplexers and antennas [4] in the RF front-end due to their excellent quality factor and small footprints at radio frequency. Among various acoustic waves, the Lamb wave platform recently gained attention [5] because it has both fundamental strengths of commercial surface acoustic wave (SAW) devices and bulk acoustic wave (BAW) devices: lithographically defined resonance frequency and CMOS circuit compatibility. Fundamental Lamb mode propagating in the aluminum nitride (AlN) thin films exhibits a very high phase velocity up to 10000 m/s thus supports higher frequency operation than surface acoustic wave.[6] The exploitation of these acoustic wave technologies, however, remains in the passive domain rather than active domain, and intrinsic nonlinearity of AlN has not been utilized. Researchers have realized nonlinear acoustic coupling by external varactor circuit [7], or nonlinear permittivity coupling.[8] However, either the parametric effect is not accumulated, or the nonlinear coupling is not sufficient to realize conversion gain. In this paper, we aim at combining the non-reciprocal property of TVTL with the advanced acoustic wave technology to develop a high frequency non-reciprocal RF device loaded with AlN Lamb wave resonators for parametric amplification. Such devices are with high quality factor, efficient energy coupling and reduced device footprints. Parametric modulation effects caused by intrinsic nonlinearity of AlN is demonstrated in Lamb wave device experiment.[9] The stiffness nonlinearity is extracted from the experimental results, which are used to demonstrate the conversion gain of Lamb wave resonator based TVTL in simulations.

II. Theory

A. Non-reciprocal TVTL



(a)



(b)

Fig. 1. Non-reciprocal TVTL implementation (a) by LC Resonators (b) by Acoustic Resonators

Time-varying transmission line is typically realized by a transmission line periodically loaded with varactor diodes. Varactor diodes in each unit can be replaced by a series LC resonator to boost conversion gain [10] as shown in Fig.1(a). In this paper, we propose another novel implementation of TVTL, for combining the strength of acoustic wave platform and non-reciprocal property of TVTL.

The proposed device, as shown in Fig.1(b), consists of a transmission line periodically loaded with acoustic wave resonators. A simplified acoustic resonator model is used here for demonstrating the device concept. A more precise acoustic resonator model including parasitic will be discussed in the next subsection. Compared to an LC resonator, an acoustic resonator has better performance for its substantially higher quality factor and smaller device size.

Varactors in the acoustic resonator model represent the nonlinear mechanical stiffness in the acoustic material. This analogy comes from equations for electromagnetic waves and acoustic waves. [8] Capacitance in electromagnetics is analogous to mechanical compliance (reciprocal of mechanical stiffness) in acoustic wave. Therefore, nonlinear mechanical stiffness in acoustic material like AlN, is analogous to varactor in the resonator model, and can be exploited to create non-reciprocal and frequency conversion behavior shown in traditional TVTL.

B. Lamb wave resonator

To launch the pump acoustic wave and the signal acoustic wave together without adding additional diplexers, a novel Lamb wave resonator is proposed as shown in Fig.2(a).

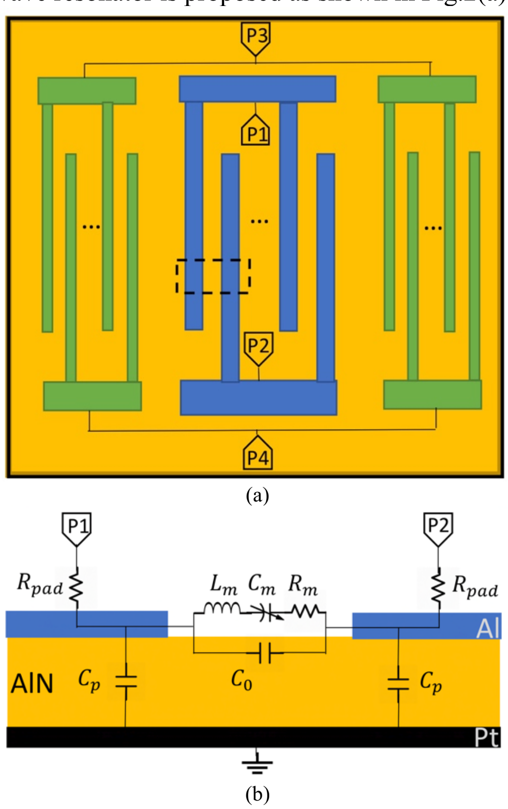


Fig. 2. Lamb wave resonator structure and model. (a) Top view. (b) IDT cross section and equivalent circuit of dashed line region in (a).

The four-port Lamb wave resonator consists of an input port P1 and an output port P2 for signal acoustic wave at ω_s, and pumping port P3 and P4 for pump acoustic wave at ω_p. Interdigital transducer (IDT) in blue has pitch and spacing of $\lambda_s/4$ for signal wave excitation, and IDT in green has pitch and spacing of $\lambda_p/4$ for pump wave excitation. Spacing between two pump transducers is designed to maximize pump wave at the center of signal transducer for enhancing parametric effects. The resonance condition for signal acoustic wave is created by etching AlN surrounding the resonator, thus forming edge reflectors. The pump acoustic wave will modulate the signal acoustic wave through the nonlinear mechanical stiffness of AlN thin film, generating mixing waves at ω_{p-s} and ω_{p+s}. Mixing wave at ω_{p-s} is designed to fall into the operation bandwidth of resonator therefore it can be received by output port P2.

Hybrid Pi-type Butterworth-Van Dyke (PiBVD) model [11] is employed to model the behaviour of Lamb wave resonator. Fig.2(b) shows the cross section of IDT and circuit model of dashed line region in Fig.2(a). Each circuit element is the parallel combination of all sub elements that appear between the top metal fingers and the bottom electrode. L_m, C_m, R_m represent the motional arm of acoustic resonance, C_0 represent IDT finger capacitance, R_{pad} represents pad resistance, C_p represents capacitance between IDT and bottom Pt layer.

III. Results

A. Simulation

Full wave simulation for the Lamb wave resonator solving piezoelectric constitutive equation is developed using COMSOL Multiphysics. The PiBVD circuit model for Lamb wave resonator is built in the Advanced Design system (ADS). Fig. 3 shows resonance behaviour of proposed Lamb wave resonator using both circuit model and full wave simulation. Series resonance at 453MHz and parallel resonance at 456MHz are predicted by both models. Mechanical displacement of Lamb wave resonance mode at 453MHz is observed by full wave simulation and plotted in Fig. 3.

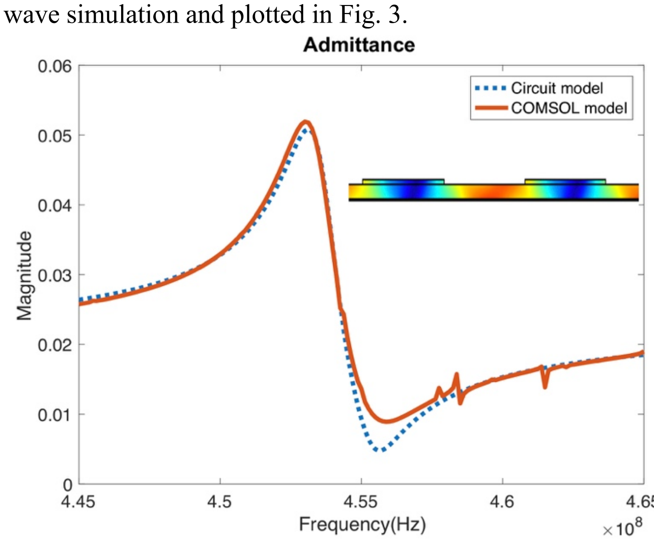


Fig. 3. Lamb wave resonator simulation using circuit model and full wave model

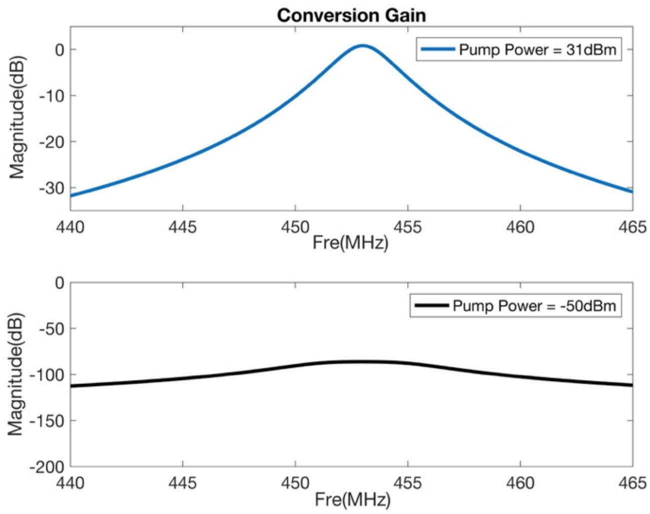


Fig. 4. Lamb wave resonator conversion gain simulation

L_m	C_m	R_m	C_0	R_{pad}	ζ
1.6uH	76.0fF	9.9Ω	8.1pF	5.4 Ω	0.003

Table 1. Circuit parameter of PiBVD model for Lamb wave resonator

Circuit parameters of the PiBVD model for the Lamb wave resonator are shown in Table 1. The varactor model ($C = C_0 + \zeta C_m V$)is built based on the nonlinearity of AlN, where ζ is obtained through the correlation with the experimental results in the next section.

To simulate parametric amplification effects, signal wave at 452MHz and pump wave at 906MHz are both launched to the resonator model. The pump wave modulates the signal wave through the nonlinear permittivity of the varactor, resulting in mixing of the Lamb wave at 454MHz that falls into the operation bandwidth of receiving port. Conversion gain is calculated by the ratio of converted mixing power over input signal power. The conversion gain plot is obtained by sweeping signal frequency from 440MHz to 465MHz. As shown in Fig.4, conversion gain can reach a maximum of 1dB with 31dBm pump power. Conversion gain drops to almost zero when the pump power is small, e.g., -50dBm.

B. Experiment

Parametric effects by nonlinear stiffness of AlN thin film have been demonstrated in the Lamb wave device conversion gain measurement. Fig.5 shows a microscope image of a fabricated Lamb wave device and the conversion gain measurement setup. The Lamb wave device has three sets of IDTs which excite the signal Lamb wave at 460MHz (middle IDT), pump Lamb wave at 587MHz (left IDT), and receive up-converted Lamb wave at 1047MHz (right IDT), respectively. When the signal Lamb wave travels in the same direction with pump Lamb wave, the signal Lamb wave is modulated by the strong pump Lamb wave through the nonlinearity of AlN. This nonlinearity results in mixing of the Lamb waves generated by parametric effects and the upconverted Lamb wave is picked up by the receiving port.

The measurement uses the mixer mode of a VNA. The signal power is -10dBm and pump power varies from -5dBm to 5dBm. The conversion gain plot is obtained by sweeping the signal frequency from 440MHz to 480MHz. The results are displayed as the ratio of received upconverted power to the input signal power.

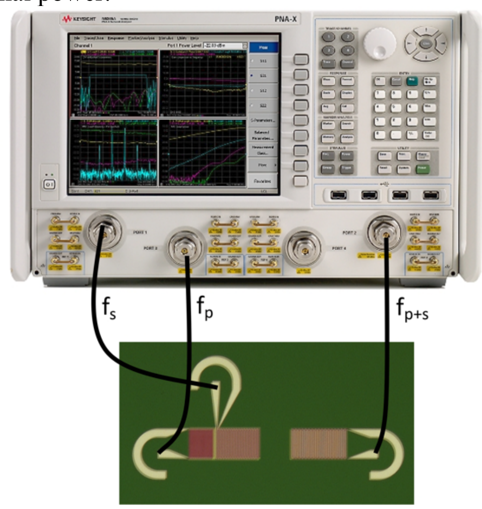


Fig. 5. Lamb Wave device under microscope and measurement setup

Conversion gain with pump powers of -5dBm, 0dBm and 5dBm are plotted in Fig.6. Conversion gain reaches -47dB when the pump power is 5dBm. This experiment serves as proof of the nonlinearity in AlN thin films and demonstrates the parametric effects in Lamb wave devices. Since the fabricated Lamb wave devices do not have a resonator structure and do not accumulate the parametric effects, low conversion gain is expected. This experiment provides the evidence of the nonlinearity of AlN to correlate with the varactor model in Lamb wave resonator simulation. Based on the simulation result, conversion gain will be substantially increased by employing our proposed Lamb wave resonator structure. Following works include fabricating Lamb wave resonators and demonstrating non-reciprocity.

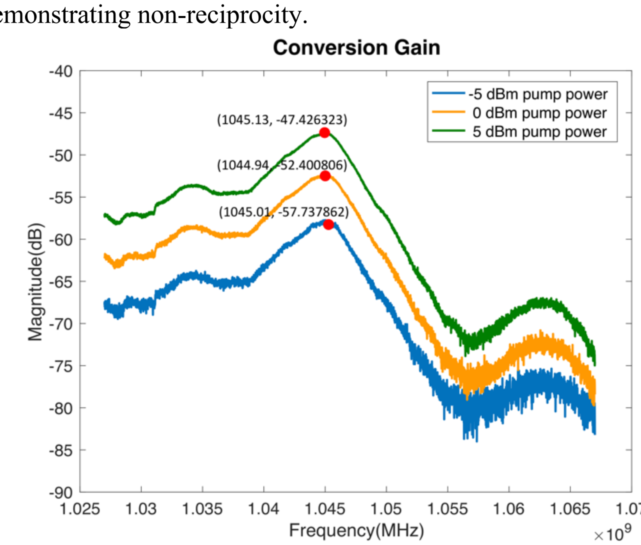


Fig. 6. Lamb wave transducer device conversion gain

IV. Conclusion

This work explores parametric amplification on the Lamb wave acoustic platform for the purpose of developing nonlinear devices and non-reciprocal devices at a reduced footprint and high quality factor. Novel Lamb wave resonator structure and non-reciprocal device implementation have been proved in theory and simulation. Nonlinearity in AlN thin film and parametric effects in Lamb wave devices have been demonstrated in experiment.

Acknowledgment

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