ACOUSTOELECTRIC-DRIVEN FREQUENCY MIXING IN MICROMACHINED LITHIUM NIOBATE ON SILICON WAVEGUIDES

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2023 IEEE 36th International Conference on Micro Electro Mechanical Systems (MEMS) | 978-1-6654-9308-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/MEMS49605.2023.10052257

ABSTRACT

This work reports on frequency mixing due to phonon-electron coupling (acoustoelectric effect) in lithium niobate (LN) on silicon (Si) micromachined Lamb mode waveguides. To study passive RF signal mixing in micro-acoustic domain, two-tone measurements are performed on said heterostructured waveguides. The results confirm the mixing is mainly due to the charge carriers in Si and is intensified as the input power level is increased. Furthermore, the mixed frequency components that lie outside of the design passband of the waveguide are also detected which is an indication of strong acoustic mixing. The preliminary results confirm the possibility of using the phonon-electron coupling in properly designed LN-on-Si waveguides for implementation of micro-acoustic mixers.

KEYWORDS

Acoustoelectric, frequency mixing, Lamb waves, lithium niobate, piezoelectric.

INTRODUCTION

The quest for realizing radio frequency (RF) frontend modules entirely in the micro-acoustic platform has intensified owing to the unprecedented efficiency and miniaturization that is inherent to this platform. Today, micro-acoustic filters have become a ubiquitous component in RF frontend modules. Said filters, which are passive devices, are currently integrated with active components to form the RF frontend module which comes at the cost of size, complexity, and performance, especially due to the multi-chip nature of these modules and the associated interconnects.

It has been shown that electrical or mechanical modulation of micro-acoustic devices could enable new functionalities that can be used for implementation of frequency tunable filters [1], non-reciprocal devices [2], and even amplifiers [3]. The amplification in the acoustic domain has been demonstrated using phonon-electron interactions known as the acoustoelectric effect (AE) [4]. This was discovered after initial observation of acoustic loss due to energy transfer to nearby charge carriers which later leveraged into acoustic wave amplification by using charge carriers to give up energy to the acoustic waves. First bulk waves in piezoelectric semiconductors and later surface acoustic waves (SAW) in layered piezoelectric-semiconductor structures were employed for said purpose. The latter allowed for tailoring the piezoelectric and semiconductor properties independently, thus improving the overall device performance. As a result of the promising results attained by layered SAW platform in conjunction with high performance piezoelectric materials such as lithium niobate (LN), AE SAW devices are even presently investigated by researchers [5, 6]. However, SAW platform faces limitation in terms of efficiency, loss, bandwidth, and transition into higher frequencies. To overcome such problems, Lamb waves in micromachined waveguides made of piezoelectric on semiconductor have been explored as a potential solution [7]. In this platform, Lamb waves generated due to the piezoelectricity are coupled to charge carriers in the semiconductor, such as silicon (Si), leading to the generation of space-charge wave. Through application of a drift field to the space-charge wave so that their drift velocity exceeds the Lamb wave phase velocity, Lamb wave amplification could occur.

Another interesting aspect of this phenomenon is that the generated space-charge can interact with acoustic waves at other frequencies and produce strains at the sum or difference frequencies which could be significant once the nonlinear phonon-electron coupling is strong. This could enable implementation of frequency mixers within the micro-acoustic domain. Since LN-on-Si platform has shown promising results in terms of phonon-electron coupling for Lamb waves, it is expected to provide strong mixing of acoustic waves, therefore, it is investigated in this work. Previously frequency mixing in the micro-acoustic domain has been demonstrated using coupled mechanical resonators [8].

To investigate said electron-mediated mixing of acoustic phonons, ultra-high frequency LN-on-Si Lamb mode waveguides are fabricated and tested using a two-tone setup as described in following sections and the results are compared with that of identical LN-only waveguides to isolate the effect of phonon-electron coupling on mixing.

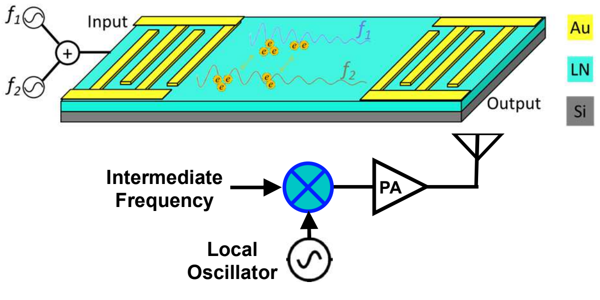

Figure 1: Conceptual schematic of wave mixing in phonon-electron coupled waveguide made of LN-on-Si and example application of a mixer in an RF transmitter.

DEVICE DESIGN & FABRICATION

The Lamb mode waveguide is fabricated on bonded LN on Si substrates having 1 µm LN on 1 µm Si with a resistivity of 5-10 Ω.cm which is chosen to enable strong phonon-electron interactions. X-cut LN is selected, and the waveguides are oriented along the ~30° off Y-axis of LN to harness the highest electromechanical coupling for fundamental symmetric (S0) mode [9]. This is crucial in maximizing the phonon-electron interactions and subsequently the frequency mixing. Interdigital transducers (IDT) with chirped design [10] are placed at the two ends of the waveguide to convert the RF signal from electromagnetic domain to acoustic domain at the input port and from acoustic domain back to the electromagnetic domain at the output port. Since the waveguides of this work are for proof-of-concept, they lack two separate ports for the input signal, instead the two tones are externally combined and fed into the input port. The waveguides have a footprint of ~300×800 μm^2 and a passband frequency of ~600 MHz as defined by the periodicity of the IDTs.

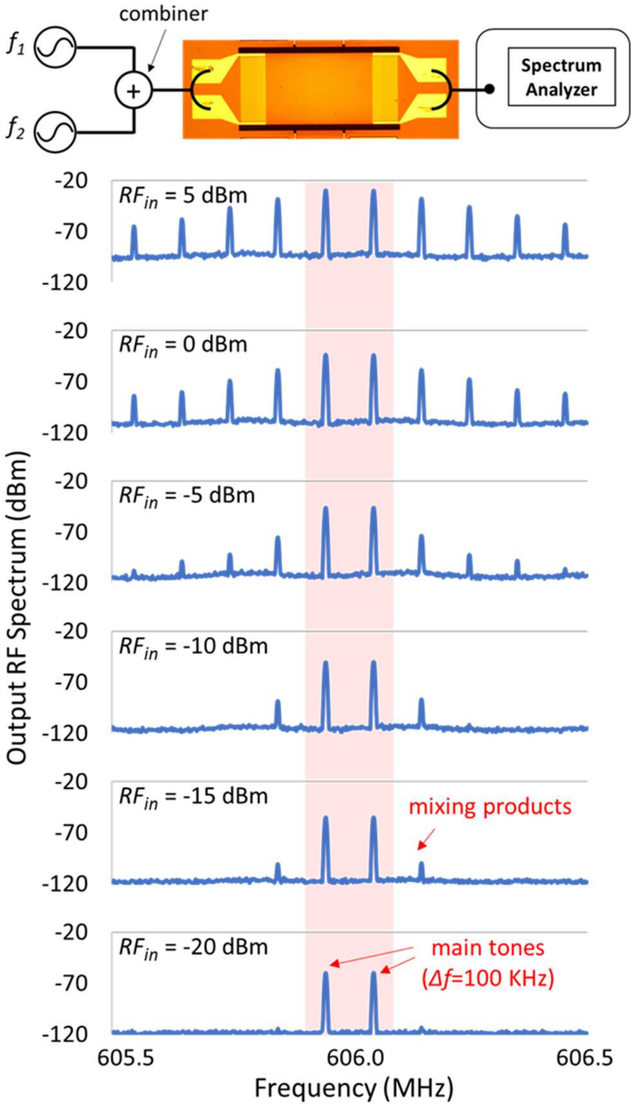

Figure 2: Micrograph of the waveguide under test and the test setup (top). Output frequency spectrum of the LN-on-Si waveguide under two-tone test as the input power is increased, resulting in stronger mixing (bottom).

EXPERIMENTAL RESULTS

The frequency mixing is demonstrated by performing two-tone tests on fabricated waveguides in room temperature and air. The test setup and the micrograph of the waveguide under test is shown in Figure 2. For a waveguide having a passband at ~600 MHz, the output of the two RF generators (Rohde & Schwarz SMC100A) are set at 605.95 MHz and 606.05 MHz and the combined signal is fed to input port IDT. The amplitude of the input RF power is swept, and the output spectrum is measured by a spectrum analyzer (Rohde & Schwarz FSUP). The output spectrum for an input RF power sweep from -20 dBm to 5 dBm is shown in Figure 2. While at low levels of input RF power, the mixing products of the two tones are insignificant, as the input RF power is increased the mixing products start to intensify which can be attributed to increased electron bunching since increasing the power, up to a certain point, results in a stronger space-charge wave, therefore, intensified acoustic wave mixing. At this point the third order product can reach as high as -8.6 dBc.

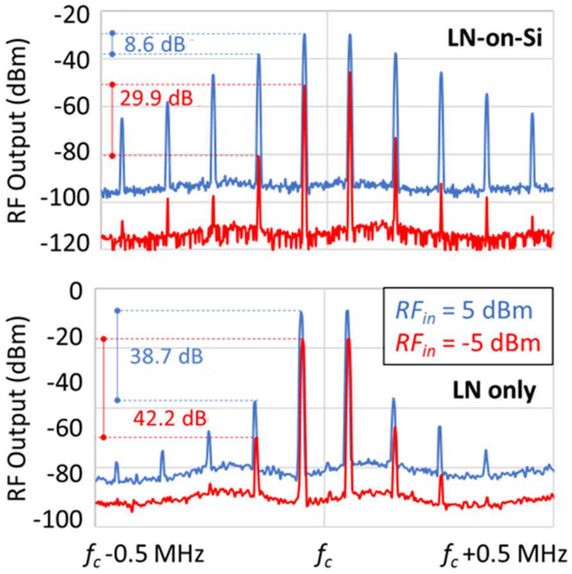

Figure 3: Output frequency spectrum of waveguides made of LN only and LN-on-Si at two input power levels (-5 and 5 dBm) showing much stronger mixing due to presence of Si.

The two-tone test is repeated after a backside etch step to completely remove the Si layer from underneath LN so that the phonon-electron mixing is isolated from other nonlinear processes which could cause frequency mixing. The output RF spectrum of the waveguide before and after the Si etching step is shown in Figure 3 top and bottom, respectively. The presence of Si results in -8.6 dBc and -29.9 dBc third order products for 5 dBm and -5 dBm input tones, respectively. On the other hand, the same for LN only waveguide is at -38.7 dBc and -42.2 dBc. This confirms that the origin of mixing is mainly due to the phonon-electron interactions within the heterostructure. The mixing products are not limited to only the design passband of the waveguide and can be observed at sum and difference frequencies of the two tones which are far from the passband of the IDT. This is shown in Figure 4 for two tones at 605 and 607MHz where the frequency mixing products at 2 MHz and 1212 MHz are present roughly at levels of -40 dBc and -50 dBc, respectively despite the large transducer loss at those frequencies.

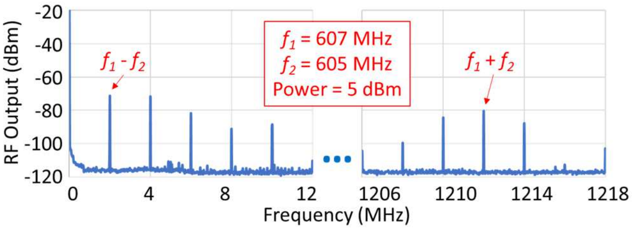

Figure 4: Output frequency spectrum of the LN-on-Si waveguide for two-tone test at 5 dBm input showing mixing products at the sum and difference frequencies.

The frequency mixing can be further enhanced by applying a bias voltage to Si layer for electron drift. This is shown in Figure 5 for a bias of 28 V (bias points marked); the transmission loss is improved through AE amplification and the mixing products are intensified, especially those that are further from the carrier. The reason for this is believed to be the saturation of AE amplification at higher acoustic powers.

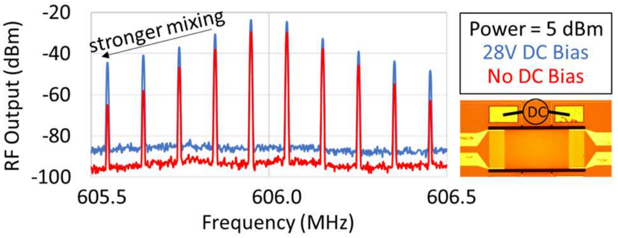

Figure 5: Output frequency spectrum of the LN-on-Si waveguide for two-tone test at 5 dBm without/with application of DC bias for electron drift; mixing is intensified at 28 V especially for the products that are further away from the carrier.

CONCLUSION

It was experimentally demonstrated that the phonon-electron coupling known as the acoustoelectric effect can lead to passive frequency mixing in lithium niobate on silicon Lamb mode waveguides. The frequency mixing is mediated by space-charge waves in the silicon layer and becomes stronger by increasing Lamb wave amplitude up to a certain point. The results indicate possibility of leveraging the phonon-electron coupling in such platform to realize RF mixers. By optimizing the transducers and propagation directions of waves, the performance of the mixer could be enhanced, thus enabling a micro-acoustic solution for this important RF communication component.

ACKNOWLEDGEMENTS

The authors would like to thank NGK Insulators for providing bonded lithium niobate on silicon substrates. This work was supported by the National Science Foundation under Grant 2122670.

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