Low-Loss 5-GHz First-Order Antisymmetric Mode Acoustic Delay Lines in Thin-Film Lithium Niobate

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Abstract—In this work, we present the low-loss acoustic delay lines (ADLs) at 5 GHz, using the first-order antisymmetric (A1) mode in 128° Y-cut lithium niobate thin films. The ADLs use a single-phase unidirectional transducer (SPUDT) design with a feature size of quarter acoustic wavelength. The design space is analytically explored and experimentally validated. The fabricated miniature A1 ADLs with a feature size of 0.45 μm show a high operating frequency at 5.4 GHz, a minimum insertion loss (IL) of 3 dB, a fractional bandwidth (FBW) of 1.6%, and a small footprint of 0.0074 mm². The low IL and high operating frequency have significantly surpassed the state-of-the-art performance of ADLs. The propagation characteristics of A1 acoustic waves have also been extracted. The demonstrated designs can lead to low-loss and high-frequency transversal filters for future 5G applications in the sub-6-GHz bands.

Index Terms—Acoustic devices, delay lines, 5G mobile communication, microelectromechanical systems, piezoelectric devices, thin-film devices, transversal filters.

I. INTRODUCTION

T

HE development of fifth-generation (5G) New Radio (NR) has been calling for unprecedented signal processing capabilities at radio frequency (RF) [1], [2]. Particularly, the enhanced mobile broadband (eMBB) [3] require new components at higher frequencies for the recently released bands [4], [5]. RF acoustic elements, leveraging the technical benefits of the acoustic domain [6], hold great potentials for chip-scale and low-loss signal processing [7], [8]. The shorter acoustic wavelengths [6] lead to orders of magnitude smaller resonant structures than their EM counterparts, while the low damping of acoustic waves enables efficient passives. Thanks to both unique features, thin-film bulk acoustic resonators (FBARs) and surface acoustic wave (SAW) devices have become ubiquitous in 4G filters [6]. However, it is challenging to scale the incumbent acoustic platforms to the 5G bands above 4 GHz, unless resorting to complex designs [9], [10], intrinsically high-damping modes [11], [12], or higher-cost substrates [13]–[15].

Recently, first-order antisymmetric (A1) mode resonators in single-crystal lithium niobate (LiNbO3) thin films have been demonstrated for sub-6-GHz acoustic filters [16]–[19]. These devices have remarkable electromechanical coupling ($K^2 > 30\%$), low damping, and high operating frequencies. Their reported ladder filters show a fractional bandwidth (FBW) as high as 10% around 5 GHz [17], [18], meeting the challenging FBW requirements for several 5G bands [5]. Despite the record-breaking performance of these filter solutions, two drawbacks currently exist for designing filters for other frequency bands with smaller FBW, such as the proposed Wi-Fi six bands at 6 GHz (2.6% FBW) [4] and the 4.8-GHz 5G band in Asia (2.1% FBW) [5]. First, the footprints of the A1 resonator-based filters are large, which is caused by the small capacitance per unit area in A1 resonators. Such a drawback worsens when in-band spurious mode suppression approaches are used [17]. Second, narrowband filters underutilize $k^2$ of A1 in LiNbO3 and require complex topologies for low IL and shape factors [20].

To this end, transversal filters based on acoustic delay lines (ADLs) are encouraging alternatives for narrowband filters. Acoustic transversal filters were first introduced in SAW platforms using single-phase unidirectional transducers (SPUDT) [21]–[25]. Their advantages lie in the excellent flexibility in defining the passband and roll-off through weighting transduction and reflection across the input and output transducers [23], [24]. However, conventional SAW ADLs are intrinsically limited to very small FBW and low operating frequencies. First, the moderate $K^2$ (<10%) and the insufficient reflector efficiency in SAW platforms fundamentally bound the lowest IL for a given FBW [22]. Second, the slow phase velocities ($v_p < 5 \text{ km/s}$) of the incumbent SAWs require narrow electrodes for high-frequency transduction, which causes severe electrical loading and limits the operating frequency to below 2.5 GHz [25]. Recently, leveraging the larger $k^2$ and reflection per wavelength of plate wave modes in thin-film LiNbO3, ADLs have been demonstrated using fundamental shear-horizontal (SH0) [26]–[28] and fundamental symmetric (S0) modes [29]–[31], achieving notably lower insertion loss (IL) and wider FBW between 0.1 and 2 GHz. Nevertheless, it remains difficult to further scale the operating frequencies above 4 GHz. To address the issues, the A1 mode in LiNbO3 with high phase velocities has been exploited to demonstrate ADL at 5 GHz while only requiring a large feature size of 500 nm [32]. However, the A1 ADL prototypes still suffer from 6-dB bidirectional transducer loss and severe in-band...
ripples from the reflections between transducers, which has kept acoustic transversal filters in 5G bands elusive.

In this work, we aim to demonstrate the first group of A1 ADLs with SPUDTs for the transversal filter application. The characteristics of A1 and the ADL design space are analytically explored and experimentally validated. The fabricated device with a feature size of 0.45 μm shows a center frequency at 5.4 GHz, a minimum IL of 3 dB, a 3-dB FBW of 1.6%, and a footprint of 0.0074 mm². The propagation loss (PL) and the group velocity of A1 are also extracted as 0.0182 dB/μm at 5.4 GHz. This article marks the first step toward ADL-based transversal filters for sub-6-GHz 5G applications.

This article is an extension of [1], which reports the baseline device measurement. In this article, we have included a detailed analysis of unidirectional transducer design, piezoelectric substrate orientation selection, and key design parameters. Compared to the state-of-the-art ADLs with similar feature sizes, this article presents a substantial enhancement in both the IL (4.9 dB less) [32] and operating frequency (3 times higher) [26], [27], [29], [30]. It is organized as follows. Section II first introduces the design of A1 SPUDT and identifies the key parameters. Section III presents the implemented device. Section IV shows the measured results and discussions. Finally, Section V states the conclusion.

II. DESIGN AND SIMULATION
A. Design Overview

The schematic of the A1 SPUDT ADL is shown in Fig. 1(a) with the key parameters listed in Table I. The ADL consists of 50-nm aluminum electrodes on top of a suspended 540-nm 128° Y-cut LiNbO₃ thin film. The thickness of the LiNbO₃ is selected to enable a center frequency around 5 GHz, while the thickness of aluminum is chosen to avoid notable cutoff of aluminum that confines acoustic waves and prevents propagation [32]. The orientation selection will be shown in Section II-B.

A pair of SPUDTs, composed of cascaded unidirectional transducer cells, are placed on the opposite ends of the suspended film. The release windows are included on the side for releasing the structure and defining the acoustic waveguide. The transducer cell design [see Fig. 1(b)] is adapted from the previously reported high-frequency SAW SPUDT [25], where the cell length \( L_c \) is two lateral wavelengths (\( \Lambda \)). \( \Lambda \) is selected as 1.8 μm to place the passband above the cutoff frequency of A1 [32]. Each cell includes a pair of transduction electrodes \( L_E = \Lambda/4 \), connected to the signal and ground, respectively, and a floating electrode \( L_F = \Lambda/2 \) [33]. In short, the asymmetric arrangement of the electrodes within a cell leads to different phase delays for the waves reflected by adjacent reflectors. By placing and sizing the electrodes properly, the waves propagating to the right (forward direction, FWD) constructively interfere with each other. On the other hand, the waves propagating toward the left (backward direction, BWD) destructively interfere with each other. The design can be analyzed by involving the reflection center (RC) and transduction center (TC) [22], [26]. In Section II-A, the acoustic wavelengths are assumed the same in the metalized and unmetalized areas. Further validation and optimization will be presented in Section II-D using finite element analysis (FEA).

RC is the equivalent position for the overall reflection within a transducer cell when the multireflections are combined [22], [26]. Reflections happen at the boundaries between the metalized and unmetalized areas, and the phase of the step-up reflections \( \Gamma_{su} = -\pi/4 \) [26]. For a single electrode, two edges both generate reflections for acoustic waves. Based on the multireflection theory [34], one can show that the overall reflection \( \Gamma_{ele} \) happens in the center of each electrode, as [26]

\[
\Gamma_{ele} = \Gamma_{su}e^{j\alpha} \frac{1 - e^{-j2\alpha}(1 - \Gamma_{su}^2)}{1 - \Gamma_{su}^2 e^{-j2\alpha}}
\]

where \( \alpha \) is the width of the reflector. The \( \Lambda/2 \) floating electrode is nonreflective, similar to the EM microstrip case [34], while the phase of \( \Gamma_{ele} \) in the \( \Lambda/4 \) electrodes is \( -\pi/2 \). Thus, it can be found that RC lies in the middle of the transduction electrode pair (blue dashed line in Fig. 1), \( \Lambda/4 \) from the center of the transduction electrodes. Using the reflection coefficient transformation theory [34], one can show the overall reflection

| Sym. | Parameter | Value | Sym. | Parameter | Value |
|------|-----------|-------|------|-----------|-------|
| A    | Lat. Wavelength (μm) | 1.8  | N    | Number of cells | 10   |
|     |           |      |     | Float. electrode length (μm) | 0.9  |
|     |           |      |     | LC         | 3.6  |
|     |           |      |     | Gap length (μm) | 20   |
|     |           |      |     | Transl. length (μm) | 36   |
|     |           |      |     | Wa        | 50   |
|     |           |      |     | Ld        | 70   |
|     |           |      |     | Le         | 0.45 |
|     |           |      |     | Lc         | 0.45 |

Fig. 1. (a) Mock-up of an A1 mode ADL with a pair of SPUDTs on a suspended LiNbO₃ thin film. (b) Top view and (c) side view of a unidirectional transducer unit cell. The labeled key parameters are listed in Table I.
coefficient of the transducer cell $\Gamma_{\text{cell}}$ as

$$\Gamma_{\text{cell}} = 2e^{i2\pi/2}/\Gamma_{\text{ele}} = -2\Gamma_{\text{ele}}.$$  

(2)

Therefore, the equivalent reflection happens in the middle of the transduction electrode pair with a phase of $\pi/2$. Notably, it is independent of the $\Lambda/2$ electrode.

TC is the node of the generated stress field [22, 26]. Different from the conventional SPUDTs, TC is away from the center of the transduction electrode due to the existence of the floating electrode, and the amount of the shift is determined by the spacing between the transduction and floating electrodes ($L_S$). Thus, the spacing between TC and RC can be tuned by placing the floating electrodes differently. FEA in Section II-D shows that the TC (red dashed line in Fig. 1) of the presented design ($L_S = \Lambda/4$) is at $\Lambda/8$ from the RC.

After launching from TC, the acoustic wave propagating toward the left gets partially reflected from RC and starts traversing toward FWD. As the reflected acoustic wave returns to TC, it experiences a constructive interference that results from $-0.5\pi$ propagation phase delay and a $0.5\pi$ phase delay from the reflection. Similarly, one can prove that destructive interference happens for the wave propagating toward BWD [26]. If equipped with enough cascaded cells ($N$), unidirectional acoustic transduction can eliminate the bidirectional loss. In operation, RF signals are transduced into acoustic waves at Port 1, unidirectionally launched toward Port 2 before being converted back to the EM domain. The transfer function in A1 due to the overmode nature in the thickness direction [32]. For a 540-nm LiNbO$_3$ thin film, the cutoff frequencies are $3.23$ GHz for $f_{\text{short}}$, and $4.10$ GHz for $f_{\text{open}}$. Both $f_{\text{short}}$ and $f_{\text{open}}$ increase for larger $\beta$. To demonstrate transversal filters based on propagating acoustic waves, one need to operate beyond the cutoff by using larger $\beta$ [32]. The phase velocity $v_p$, group velocity $v_g$, and $K^2$ at different $\beta$ can be calculated by [38], [39]

$$v_{p, \text{short}} = 2\pi f_{\text{short}}/\beta, v_{p, \text{open}} = 2\pi f_{\text{open}}/\beta$$

(4)

$$v_{g, \text{short}} = 2\pi \partial f_{\text{short}}/\partial \beta, v_{g, \text{open}} = 2\pi \partial f_{\text{open}}/\partial \beta$$

(5)

$$K^2 = (v_{p, \text{open}}/v_{p, \text{short}})^2 - 1.$$  

(6)

The obtained values are plotted in Fig. 3(b)–(d), respectively. A maximum $K^2$ of 61.3% is obtained near the cutoff. The FEA obtained $K^2$ is different from that calculated earlier because the quasi-static assumption is no longer used [35]. High phase velocities beyond 10 000 m/s, low group velocities below 5000 m/s, and more importantly, high $K^2$ over 8% are obtained for $\Lambda$ over 1.8 $\mu$m (or $\beta$ less than 3.5 $\mu$m$^{-1}$), enabling the simultaneously high frequency and wideband acoustic transduction. With a larger $\beta$, the operating frequency increases with declining $K^2$. Thus, the design tradeoff exists between large $K^2$ and high operating frequencies. This work, aiming to demonstrate the first low-loss ADL beyond 5 GHz, uses 1.8 $\mu$m $\Lambda$ ($\beta$ of 3.5 $\mu$m$^{-1}$).

C. A1 SPUDT ADL Baseline Design

After obtaining the transduction and propagation properties of A1, a baseline design in Table I is first studied using FEA. A 2-D simulation is set up following the process in [30]. The 2-D FEA assumes A1 waves propagating along the $X$-axis and neglects the effects in the busline area. Such simplifications

![Image](313x593 to 562x741)

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**Fig. 2.** (a) Vibrational mode shape of A1. (b) Comparison of coupling coefficients ($K_{15}^2$) in rotated Y-cut LiNbO$_3$ substrates with rotation $\Psi$. The dependence of the in-plane orientations ($\lambda$) is shown with different curves. The orientations used in prior reports are marked.
have been validated in [32]. A pair of SPUDTs are placed on the top of the suspended LiNbO3 thin film. Perfectly matched layers (PMLs) are placed on the ends for absorbing the energy leakage from the ADL. Mechanically free and electrically open boundary conditions are assigned to the top and bottom surfaces. The structure is assumed lossless in the simulation because the damping sources in A1 devices have not been well studied and are still under investigation [32].

The S-parameters are plotted in Fig. 4(b) with both ports conjugately matched to $101 + j82$ Ω. For an ADL with a large feature size of 0.45 μm, an IL of 1.33 dB, a 3-dB FBW of 1.75%, and a center frequency of 5.37 GHz are attained. The high operating frequencies and the low IL remarkably surpass the state-of-the-art. The low IL further confirms the unidirectionality of the proposed SPUDT in Section II-A.

The susceptibility of the center frequency to fabrication variation is also studied through FEA. Different from fundamental Lamb waves (e.g., S0), the operating frequency of A1 is collectively determined by both the lateral and thickness dimensions [32]. The frequency shifts for 1% variations in the LiNbO3 thickness, aluminum thickness, and lateral wave-length are 0.47%, 0.04%, and 0.47%, respectively. Accurate frequency setting might require similar trimming and compensation schemes that have been adopted for other acoustic technologies [41].

### D. A1 SPUDT Optimization

In this subsection, we will validate the baseline design as optimal for 5-GHz A1 SPUDT ADLs in the current film stack. Four key parameters are studied, including the spacing length $L_S$, floating electrode length $L_F$, transduction electrode length $L_E$, and aluminum thickness $T_{Al}$, using parametric FEA. One parameter is adjusted at a time, while the other dimensions remain the same as listed in Table I.

First, the effects of $L_S$ are studied [see Fig. 5(a) and (b)], which directly determines the spacing between RC and TC. When $L_S$ deviates from the optimal value of 0.5λ, larger IL is observed because the reflected waves propagating toward FWD no longer match the phase of the directly generated phase, leading to insufficient directionality. Second, the effects of $L_F$ are studied [see Fig. 5(c) and (d)]. If the dimension differs from 0.5λ, the floating electrode is no longer nonreflective. Larger IL and increased ripples are observed because the reflection in the floating electrode shifts $RC$. Besides, the device with a lower metal coverage ratio has a higher operating frequency due to less metal loading. Third, the impact of $L_E$ is plotted in Fig. 6(a) and (b). Similar to the case of
Fig. 5. Simulated (a) IL and (b) RL of A1 SPUDT ADLs with different LS. Simulated (c) IL and (d) RL of A1 SPUDT ADLs with different LF.

**TABLE II**

| Index   | $\Lambda$ (\(\mu\)m) | $L_E$ (\(\mu\)m) | $N$ | Sim. (Fig.) | Meas. (Fig.) | Comments                  |
|---------|-----------------------|------------------|-----|-------------|--------------|--------------------------|
| Baseline| 1.8                   | 20               | 10  | 4           | 11           | A1 SPUDT ADL Prototype   |
| Group A | 1.8                   | 20               | 5   | 7           | 13           | Different FBW            |
| Group B | 1.8                   | 20-640           | 10  | 8           | 14           | Different delay, $v_p$, and PL |
| Group C | 2.0-2.2               | 20               | 10  | 9           | 15           | Different Operating Freq. |

$L_F$, a lower metal coverage ratio leads to a higher operating frequency. Otherwise, the performance is similar in terms of IL and FBW. $L_E$ of 0.25\(\mu\)A is selected because it has the most relaxed lithography feature size (0.25\(\mu\)A). Finally, the influence of $T_{Al}$ is studied [see Fig. 6(c) and (d)]. In addition to the frequency shifting, thicker metal leads to larger mechanically induced reflection per unit cell, resulting in both lower IL and more pronounced ripples [26], [32]. There is a design tradeoff between the IL and in-band ripples. Moreover, another design tradeoff also exists between the increased mechanical damping [30] and reduced electrical resistance [32] for thicker metal. We select 50 nm aluminum as top metal thickness to balance the design trades above.

### E. Key Design Parameters of A1 SPUDT ADL

Based on the A1 SPUDT design, three key design parameters, namely, the cell number $N$, gap length $L_G$, and wavelength $\Lambda$ determine the FBW, delay, and operating frequency of ADLs, respectively [32]. Three groups of devices (see Table II) will be studied using frequency domain FEA.

First, $N$ determines the FBW. An ADL with $N$ of 5 is simulated using the same set-up as in Section II-C. The S-parameters are plotted in Fig. 7(a) with both ports conjugately matched to 232 + j212. An IL of 1.96 dB, a 3-dB FBW of 3.16%, and a center frequency of 5.37 GHz are extracted. Compared with the baseline design, a much wider FBW is achieved at the cost of increased IL, agreeing with the IL-FBW design tradeoff for SPUDTs [22]. Similar to the ten-cell case, the in-band ripples are caused by the multireflections between the transducers. They are likely to be significantly mitigated in the actual measurements from the PL [30]. The wideband performance is shown in Fig. 7(c).

Second, $L_G$ sets the group delay. In addition to the baseline design with 20-\(\mu\)m $L_G$, ADLs with longer $L_G$ (40, 80, and 160 \(\mu\)m) are simulated. The IL and return loss (RL) are plotted in Fig. 8(a) and (b), respectively. IL remains the same for devices with different $L_G$ because of the lossless assumption in FEA. The group delays are presented in Fig. 8(c). In-band ripples with smaller frequency spacings are observed in devices with longer $L_G$ because the longer devices provide larger resonant cavities for the multireflections between the transducers [30]. The extracted group delays are...
plotted against $L_G$ in Fig. 8 (d). The group velocity is extracted as 4306 m/s, close to the obtained $v_{g,\text{open}}$ of 4360 m/s from FEA in Section II-B.

Finally, $\Lambda$ decides the operating frequency for ADLs in the same film stack. As presented in the dispersion (see Fig. 3), a longer lateral wavelength lowers the operating frequency. ADLs with $\Lambda$ of 2 and 2.2 $\mu$m are simulated. In Fig. 9(a), the ADL with 2 $\mu$m $\Lambda$ shows an IL of 1.12 dB, a 3-dB FBW of 1.68%, and a center frequency at 5.12 GHz. In Fig. 9(c), the ADL with 2.2 $\mu$m $\Lambda$ shows an IL of 1.35 dB, a 3-dB FBW of 1.70%, and a center frequency at 4.87 GHz. The group delays are presented in Fig. 9(b) and (d). The device with $\Lambda$ of 2.2 $\mu$m suffers from adjacent low $K^2$ spurious mode. A close examination is required for frequency-scaling A1 SPUDT ADLs as the higher number of eigenmodes per unit frequency range around higher-order acoustic modes [42] might create spurious modes.

To sum up, we present the A1 SPUDT ADLs in Section II. The wideband high-frequency operation is enabled by selecting the most efficient thin-film LiNbO$_3$ wafer cut and orientation for A1 ($X$-axis in 128 Y-cut LiNbO$_3$) and adopting a unique SPUDT design with a large feature size ($0.25\Lambda$). FEA is performed for identifying the key parameters. The designs will be experimentally validated in Section IV.

### III. DEVICE FABRICATION

The devices were fabricated following the process in [32]. A 540-nm 128$^\circ$ Y-cut LiNbO$_3$ thin film on a 4-in silicon (Si) wafer is provided by NGK Insulators, Ltd., for the fabrication. The optical images of the implemented devices are shown in Fig. 10. The release windows are on the sides of the waveguide.

Four sets of A1 SPUDT ADLs are implemented (see Table II). The first one is the baseline design [see Fig. 10(a) and (b)], aiming at low-loss wideband operation beyond 5 GHz. Besides, other devices are also implemented, showing the impact of the key design parameters. Group A [see Fig. 10(c)] includes devices with different FBW by changing $N$. Group B [see Fig. 10(d) and (e)] includes ADLs with various delays by setting $L_G$. Group C validates the frequency setting capability through lithographically changing lateral wavelength $\Lambda$. Details are listed in Table II.
IV. MEASUREMENT AND DISCUSSION

A. A1 SPUDT ADL Baseline Design

The implemented ADLs were first measured with a Keysight network analyzer at the −10 dBm power level and then conjugately matched to 153 + j129 Ω in Keysight Advanced Design System. The port impedance slightly deviates from the simulated value, with a larger real part due to the resistive loss in the electrodes and a larger imaginary part from the capacitive feedthrough between the probing pads [32]. The IL and RL are plotted in Fig. 11(a) and (b), showing a record-high center frequency of 5.4 GHz, an IL of 3 dB, and a 3dB-FBW of 1.6%. More importantly, a large feature size of 0.45 μm is used. A group delay of 11 ns is obtained in the passband [see Fig. 11(b)]. Compared to the simulation in Fig. 4(c), the measured group delay shows smaller ripples in the passband, because the multirefections are damped by the PL. The wideband performance is presented in Fig. 11(c). The device also features a compact size. The active region (the part between the release windows in Fig. 1) only occupies a footprint of 0.0074 mm². To build a 50- transversal filter, one would need to connect three of the devices in parallel (or increase the aperture width by three times), and then include an inductor of 1.1 nH (inductor Q assumed as 15) in series to cancel out the imaginary part. The added inductor would introduce an additional 0.5-dB IL. The estimated footprint for such a 50-Ω transversal filter is 0.0226 mm². When compared with resonator-based filters above 4 GHz, the A1 SPUDT ADL prototype has narrower FBW (8.1% in [15], 10% in [17], 12% in [18]), slightly worse IL (1.8 dB in [15], 1.7 dB in [17], around 1.8 dB in [18]), but significantly smaller footprint (0.557 mm² in [15], 0.36 mm² in [17], around 1 mm² in [18]). Such results mark the first step toward ADL-based transversal filters for sub-6-GHz 5G applications.

As seen in Fig. 12, the simulated results match well with the measured one after applying the parasitic components. Different approaches can be used to mitigate parasitic terms. $C_p$ can be reduced by using high resistivity substrates or differential structures [43]. $R_s$ can be improved by optimizing the quality of the deposited aluminum thin film or using devices with a shorter aperture width [32]. Design optimizations will be studied in future works.

B. A1 SPUDT ADLs With Different FBW

The ADL in Group A is fabricated and measured, showing the design with a greater FBW by implementing the same transducer design except a smaller $N$ of 5. The S-parameters are shown in Fig. 13(a) with both ports conjugately matched to 290 + j265Ω. An IL of 3.62 dB, a 3-dB FBW of 3.30%, and a center frequency at 5.4 GHz are extracted. Compared with the baseline design measurement in Fig. 12, a much greater FBW is achieved at the cost of slightly increased IL (0.6 dB), agreeing with the simulation in Fig. 7. A delay of 8 ns is extracted [see Fig. 13(b)], lower than that in Fig. 11(b), due to a shorter transducer length [30]. The wideband performance is shown in Fig. 13(c).

C. A1 SPUDT ADLs With Different Delays

Devices in Group B are designed with different delays by setting $L_G$ between 20 and 640 μm. IL and RL are plotted in Fig. 14(a) and (b), while the group delays are plotted in Fig. 14(c). The ports are conjugately matched to 153 + j129Ω. The results show an FBW of 1.6%. Devices with longer gaps have larger IL and longer delays. More specifically, the device with the largest $L_G$ of 640 μm resistance in the electrodes [32] leads to an increase of RL at higher frequencies [see Fig. 12(b)]. The difference can be modeled as a feedthrough parasitic capacitance ($C_p$) of 1.8 fF between ports, and series resistance ($R_s$) of 26 Ω at each port. As seen in Fig. 12, the simulated results match well with the measured one after applying the parasitic components. Different approaches can be used to mitigate parasitic terms. $C_p$ can be reduced by using high resistivity substrates or differential structures [43]. $R_s$ can be improved by optimizing the quality of the deposited aluminum thin film or using devices with a shorter aperture width [32]. Design optimizations will be studied in future works.
Fig. 13. Measured performance of the A1 ADL with $\Lambda$ of 1.8 $\mu$m, LG of 20 $\mu$m, and $N$ of 5. (a) IL and $RL$. (b) Group delay. (c) Wideband S-parameters.

Fig. 14. Measured performance of the A1 ADL with $\Lambda$ of 1.8 $\mu$m, LG between 20 and 640 $\mu$m, and $N$ of 10. (a) IL. (b) $RL$. (c) Group delay. (d) Extracted group delay with different LG.

[see Fig. 10(e)] shows an IL of 14.1 dB and a group delay of 163.3 ns. The extracted group delays are plotted against $LG$ in Fig. 14(d). The extracted PL is 0.0182 dB/μm, and the group velocity is 3976 m/s, both in agreement with the previously reported values [32]. The empirical correlation expression relating IL and the group delay $\tau$ for ten-cell A1 SPUDT ADL is

$$\text{IL(dB)} = 2.55 + 0.0724\tau (\text{ns}).$$

(7)

D. A1 SPUDT ADLs With Different Operating Frequencies

Devices in Group B operate at different center frequencies by using different $\Lambda$ (2 and 2.2 $\mu$m) in the same film stack. In Fig. 15(a), the ADL with $\Lambda = 2 \mu m$ shows an IL of 2.98 dB, a 3-dB FBW of 1.88%, and a center frequency at 5.15 GHz. In Fig. 15(c), the ADL with $\Lambda = 2.2 \mu m$ shows an IL of 2.74 dB, a 3-dB FBW of 1.45%, and a center frequency at 4.97 GHz. The achieved A1 passband matches the simulation.

Fig. 15. Measured performance of the A1 ADL with LG of 20 $\mu$m and $N$ of 10. (a) (b) IL and $RL$ for an ADL with $\Lambda$ of 2 $\mu$m. (c) and (d) IL and $RL$ for an ADL with $\Lambda$ of 2.2 $\mu$m.

Fig. 16. Comparison of the reported A1 SPUDT ADL to prior works (see Table I), in terms of IL and operating frequency.

Besides, fewer spurious modes exist in measurement than in simulation for the 2.2-$\mu$m case. The slight discrepancy might be caused by the material properties used in FEA differing from the actual ones. Fig. 9(b) and (d) presents the group delays, showing mitigated ripples compared to FEA due to the PL. The results show that transversal filters of different frequencies can be implemented monolithically by changing $\Lambda$ on the same LiNbO$_3$ thin film.

E. Discussions

The obtained results (Baseline and Group B) are compared with the previously reported ADLs [22]–[27], [29], [30], [32], in Fig. 16 and Table III. Thanks to the optimal orientation and the new transducer design, record-high operating frequency and lowest IL above 1 GHz have been demonstrated. More specifically, compared to the prior work using similar feature sizes (0.45 $\mu$m in this work) [27], [30], this work shows more than 3 times higher frequencies while still maintaining the same feature size. Compared to our published work on A1 using bidirectional transducers ADL in Z-cut LiNbO$_3$ [32], this work also achieves a significant IL reduction of 3.9 dB.

Finally, the loss sources in the 5.4-GHz ADL are analyzed using the simulated directionality [see Fig. 4(b)] and extracted PL (see Fig. 14). The first contributor is the 1.3 dB loss caused by the finite unidirectionality of the implemented SPUDT.
The unidirectionality can be further improved by adding more cells at the cost of a narrower bandwidth [26]. The second origin is the PL, accounting for a loss of 1 dB. The PL can be further reduced through a more compact ADL design. The remainder 0.7 dB is caused by a combination of resistive loss in the electrode and dielectric loss in the LiNbO3 film and the silicon substrate. Upon further optimization, a sub-2-dB IL with suppressed sidelobes [23] and spurious modes [40] is within reach. The implemented A1 SPUDT ADL shows the first step toward transversal filter synthesis in the sub-6-GHz 5G bands. Future work will also focus on enabling wider FBW. Potential approaches include using fewer cells in transducers or operating in the portion of the A1 dispersion curve that also corresponds to higher $K^2$ (see Fig. 3). The latter, however, requires first addressing the cutoﬀ challenge [32] through transducer and waveguide co-optimization.

V. CONCLUSION

In this work, low-loss A1 SPUDT ADLs at 5 GHz have been demonstrated in 128° Y-cut LiNbO3 thin ﬁlms. The device with a feature size of 0.45 μm shows a center frequency of 5.4 GHz, a minimum IL of 3 dB, a 3dB-FBW of 1.6%, and a footprint of 0.0074 mm². The demonstrated performance significantly surpasses the performance of state-of-the-art ADLs, addressing the long-standing challenge of efﬁciently accessing high-frequency wideband propagating acoustic waves. The described ADL technology can potentially enable low-loss, high-frequency transversal ﬁlters in the sub-6-GHz bands.

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