# X-BAND FREQUENCY SCALING OF A0 AND S0 FOCUSED LAMB MODES FOR ACOUSTIC DELAY LINES IN 30% SCANDIUM ALUMINUM NITRIDE

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## ABSTRACT

Scandium-doped aluminum nitride (ScAlN) is a high electromechanical coupling, CMOS-compatible piezoelectric material exhibiting high phase velocity Lamb modes. This work examines, for the first time, the scaling of the fundamental symmetric and asymmetric Lamb modes into the X-band with micromachined acoustic waveguides in 30% ScAlN. These modes, which are injected from focusing interdigitated transducers, converge at wavelength-scale dimensions for the application of phononic integrated circuits. We report on the high coupling and extract the propagation losses in this platform.

## KEYWORDS

Lamb modes, focusing interdigitated transducer, scandium aluminum nitride, dispersion, frequency scaling, acoustic delay lines, phononic integrated circuits.

## INTRODUCTION

The advancement of microwave systems and radio frequency front ends have required the improvement of signal processing capabilities, often enhanced by traveling acoustic wave devices. The transduction of an electromagnetic signal into the mechanical domain through the piezoelectric effect reduces the phase velocity, and therefore wavelength, by several orders of magnitude. The smaller wavelength enables passive acoustic wave devices at microwave frequencies with a compact form factor and chip-scale integration of devices. Acoustic delay lines (ADLs), a fundamental traveling wave device, have been used for various applications including sensing [1], non-reciprocal devices [2], and filters [3].

Scandium-doped aluminum nitride (ScAlN) has become a popular piezoelectric material thanks to its CMOS-compatibility and its high electromechanical coupling ($k_t^2$). Lamb waves, which are very dispersive in nature, have become a popular choice for acoustic wave devices in 30% ScAlN [4]. To maximize device performance, dispersion analysis of the piezoelectric platform must be extensively studied to optimize coupling for the operating frequency. This analysis, combined with the design of focusing interdigitated transducers (FIDTs) [5], enables the use of acoustic waveguides and subsequent development of compact phononic integrated circuits (PnICs).

As future generations of wireless communication networks become developed, the desire for frequency scaled devices become greater, with devices approaching the millimeter-wave regime [6]. Acoustic wave devices often suffer from extremely high phononic losses as they are scaled up in frequency [7]. This work, for the first time, uses FIDTs for the wavelength-scale conversion of the fundamental symmetric and asymmetric (A0 and S0) Lamb modes in 30% ScAlN operating in the X-band. A piezoelectric defined etch is used for the implementation of an acoustic waveguide for acoustic delay line applications for the analysis of propagation loss at these frequencies.

## DISPERSION ANALYSIS AND OPTIMIZATION

Dispersion describes how the propagation characteristics of a travelling change over its operating frequency. Lamb waves are inherently dispersive in nature, with their phase velocity rapidly changing. As phase velocity controls the waves electromechanical coupling [8], optimizing the operating regime of the film thickness with respect to the acoustic wavelength (*t/λ*) allows for the employment of maximal coupling. Dispersion in suspended 30% ScAlN is shown through the phase velocity over operating frequency and theoretical coupling over *t/λ*, shown in Fig. 1(a) and 1(b) respectively. The optimal point for the S0 mode falls at a *t/λ* of roughly 0.4, which is also known as the Lamé mode. This highlights the importance of optimizing the operating frequency for a given film thickness to maximize device performance. To highlight the Gaussian-like mode generation of the FIDT, the normalized total displacement at the A0 resonant frequency in 30% ScAlN is shown in Fig. 1(c), extracted using COMSOL Multiphysics, with an inset demonstrating mode convergence and propagation in the acoustic waveguide for both the A0 and S0 modes.

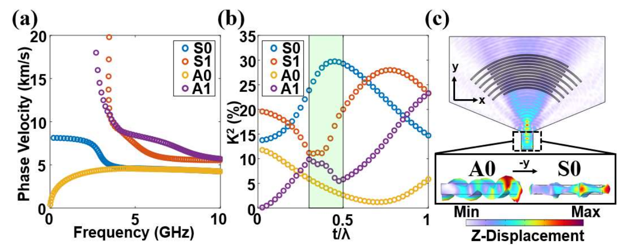


*Figure 1: Dispersion analysis of first four Lamb modes in suspended 30% ScAlN showing (a) phase velocity over operating frequency and (b) theoretical electromechanical coupling ($K^2$) over t/λ, with the operating region in this work shown in green. (c) Normalized total displacement of an FIDT demonstrating the guidance of the A0 and S0 modes in an acoustic waveguide.*

## FABRICATION PROCESS

The ADLs in this work were fabricated to possess a *t/λ* of 0.3, 0.4, and 0.5 (where coupling is maximized for the S0 mode, shown in Fig. 1(b)) for a 30% ScAlN film thickness of 280 nm on a high-resistivity silicon wafer. The film was etched using a chlorine-based reactive ion etching chemistry to expose the silicon for the released devices. Due to the small critical features, electron beam lithography was used to define the FIDT electrodes with wavelengths of 933, 700, and 560 nm with 95 nm of thermally evaporated aluminum. The probing pads were defined through optical lithography with a 5/200 nm titanium/gold sputtering. The devices were finally released using a xenon-difluoride isotropic etch, with a sample ADL shown in Fig. 2(a).

## EXPERMENTAL RESULTS

The FIDTs, having the same design parameters as in [6], were impedance matched to 500 Ω with a focal length of 20 μm. The delay line lengths varied between 50 and 250 μm with a waveguide width of 3 μm. Forward transmission, $S_{21}$, for each operating wavelength for the A0 and S0 modes are shown in Fig. 2(b), showing excellent agreement between theoretical and measured operating frequency extracted from the phase velocity in Fig. 1(a). For the device with a wavelength of 560 nm, it is clear the operating frequency of these devices extends beyond 10 GHz, well into the X-band. Propagation loss can be extracted by taking the maximum insertion loss over different delay line lengths for both the A0 and

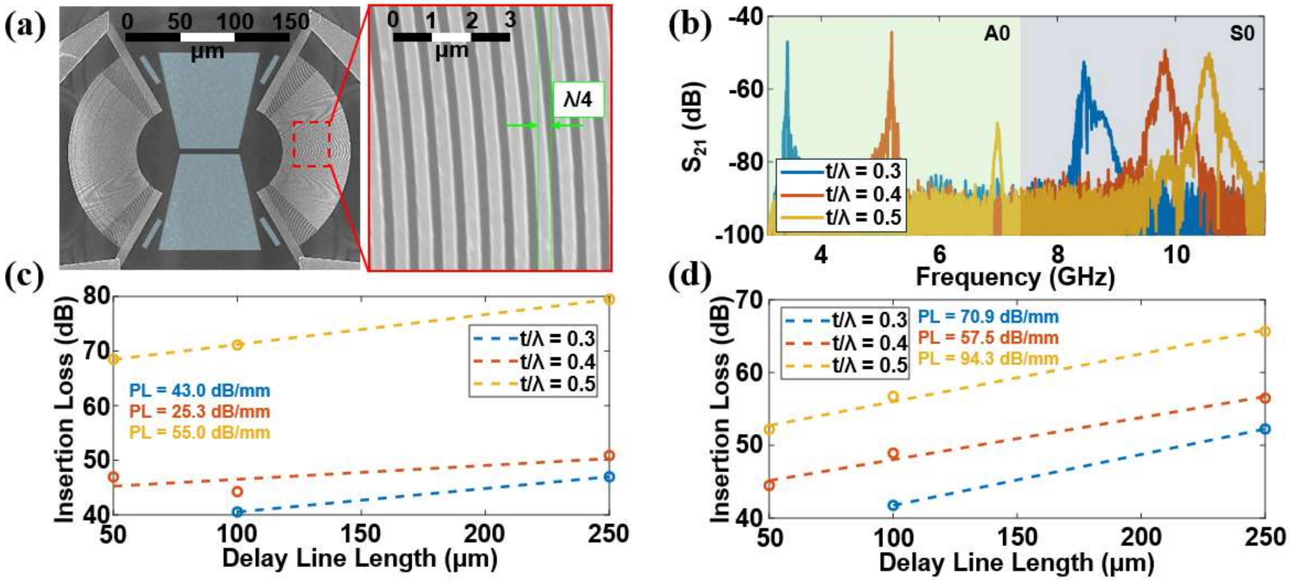


*Figure 2: (a) Scanning electron microscope (SEM) image of an X-band FIDT ADL. (b) Forward transmission ($S_{21}$) for various t/λ with a delay line length of 50 μm, demonstrating the frequency scaling of A0 and S0 Lamb modes. Minimum insertion loss over delay line length to extract propagation loss through a linear fit for the (c) A0 mode and (d) S0 mode, respectively, for a waveguide width of 3 μm.*

S0 mode. This process is shown in Fig. 2(c) and 2(d), respectively. The values of the extracted propagation loss are extracted when a waveguide width of 3 μm is implemented. For the A0 mode, the extracted propagation loss is 43 dB/mm (0.0401 dB/λ), 25.3 dB/mm (0.0177 dB/λ), and 55 dB/mm (0.0308 dB/λ), corresponding to a *t/λ* of 0.3, 0.4, and 0.5, respectively. For the S0 mode, these values are 70.9 dB/mm (0.0661 dB/λ), 57.5 dB/mm (0.0403 dB/λ), and 94.3 dB/mm (0.0528 dB/λ). Fabricated resonators on the same chip (optimized for the S0 mode) yielded a $k_t^2$ of 5.19% (0.52%), 8.05% (0.49%) and 7.54% for wavelengths of 933, 700, and 560 nm, for the S0 (A0) mode. Sources of discrepancy between the theoretical and measured coupling can be credited to losses in the metal electrodes and piezoelectric film, along with the impedance mismatch of the transducer. Across each operating wavelength, the S0 mode exhibited a higher propagation loss, likely due to its higher operating frequency, although each suffered significant losses. Although coupling is maximized through the dispersion analysis of the piezoelectric platform for the S0 mode, frequency scaling for passive ADLs is not enough to mitigate the phononic losses.

## CONCLUSION

This work frequency scaled the A0 and S0 Lamb modes to the X-band for ADLs with wavelength-scale acoustic waveguides while optimizing coupling, for the first time, in suspended 30% ScAlN. The propagation loss of each of mode at these frequencies is analyzed, showing high losses at these scaled frequencies, which limits the practicality of long time-delays. While the losses incurred at these higher frequencies are significant for passive PnICs, these results motivate the use of surface acoustic waves on solidly mounted platforms, in which losses will be significantly lower compared to Lamb waves, while also offering mechanical robustness for the integration of large scale PnICs.

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