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Low Phase Noise RF Oscillators Based on Thin-Film Lithium Niobate Acoustic Delay Lines

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Abstract—An RF oscillator has been demonstrated using a wideband SH₀ mode lithium niobate acoustic delay line (ADL). The design space of the ADL-based oscillators is theoretically investigated using the classical linear time-invariant (LTI) phase noise model. The analysis reveals that the key to low phase noise is low insertion loss (IL), large delay (τ_G), and high carrier frequency (f_o). Two SH₀ ADL oscillators based on a single SH₀ ADL ($f_o = 157\text{MHz}$, IL = 3.2 dB, $\tau_G = 270$ ns) but with different loop amplifiers have been measured, showing low phase noise of -114 dBc/Hz and -127 dBc/Hz at 10-kHz offset with a carrier power level of -8 dBm and 0.5 dBm, respectively. These oscillators not only have surpassed other Lamb wave delay oscillators but also compete favorably with surface acoustic wave (SAW) delay line oscillators in performance. [2019-0223]

Index Terms—Microelectromechanical systems, lithium niobate, acoustic delay lines, oscillator, piezoelectric transducers, phase noise.

I. INTRODUCTION

ACOUSTIC delay lines (ADL) are a versatile building block for a wide range of applications, including filters [1], environmental sensors [2], nonreciprocal components [3], and RF frequency references [4], [5]. They are conventionally built with surface acoustic wave (SAW) technology. As a promising alternative, recent efforts have been devoted to developing high-performance plate wave ADLs based on lithium niobate (LiNbO₃) thin films [6]–[8]. In contrast to SAW ADLs, LiNbO₃ plate wave ADLs show higher electro-mechanical coupling (k^2) and better reflectivity (Γ) per wavelength, which lead to significantly lower IL, wider FBW, and better center frequency (f_o) scalability over a wide range of time delay (τ_G) [9]. Such improvement can be especially beneficial to the RF oscillator design based on ADLs for either a single-mode oscillator [10] or comb frequency generator [11]. Low IL, long delay, and high f_o are the key to low phase noise (PN) and DC-power reduction, while wide FBW can be leveraged for frequency tuning.

To exploit the advances made in LiNbO₃ plate wave ADLs, we seek to demonstrate the first oscillator based on this newly

emerged delay line technology in this work. A previous developed fundamental shear horizontal (SH₀) mode VHF ADL with $f_o = 157$ MHz, IL = 3.2 dB, $\tau_G = 270$ ns, and FBW > 6% is used as the frequency selecting element [6]. Two commercially-off-the-shelf (COTS) low noise amplifiers, namely MAR-6+ and ZFL-1000LN+, are used to configure two distinct oscillator circuits with different carrier power. Finally, the oscillator performance is evaluated based on phase noise and dc-current consumption. Proposed LiNbO₃ ADL oscillators show significantly better performance than the Lamb wave ADL oscillator in literature [10], while also attaining performance comparable to commercial SAW ADL oscillators but at lower carrier power [12], [13].

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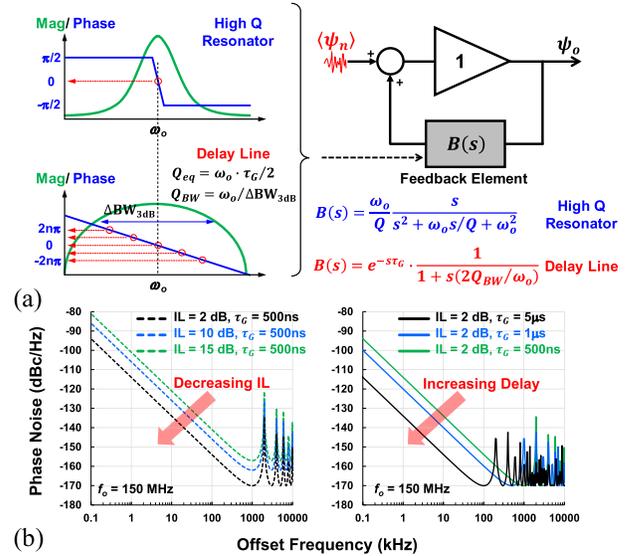


Fig. 1. (a) Schematic of the LTI phase-space model for general oscillators employed a high- Q resonator or a delay line as the frequency selection element. (b) Simulated phase noise for a 150 MHz delay line oscillator with respect to IL and delay. Assumed a wideband delay line with $Q_{BW} = 5$.

emerged delay line technology in this work. A previous developed fundamental shear horizontal (SH₀) mode VHF ADL with $f_o = 157$ MHz, IL = 3.2 dB, $\tau_G = 270$ ns, and FBW > 6% is used as the frequency selecting element [6]. Two commercially-off-the-shelf (COTS) low noise amplifiers, namely MAR-6+ and ZFL-1000LN+, are used to configure two distinct oscillator circuits with different carrier power. Finally, the oscillator performance is evaluated based on phase noise and dc-current consumption. Proposed LiNbO₃ ADL oscillators show significantly better performance than the Lamb wave ADL oscillator in literature [10], while also attaining performance comparable to commercial SAW ADL oscillators but at lower carrier power [12], [13].

II. ADL BASED OSCILLATOR

A. Phase Noise for ADL-Based Oscillator

Fig. 1(a) depicts a general phase-space model of a feedback oscillator where the feedback element can be a high- Q resonator or a delay line (DL). Unlike the high- Q resonator, a DL oscillator can operate at different modes within its bandwidth [9]. The spacing of adjacent modes is determined by the reciprocal delay time of the DL, which is given by

$$\tau_G = \frac{d\phi}{d\omega} = \frac{2Q_{eq}}{\omega_o} \quad (1)$$

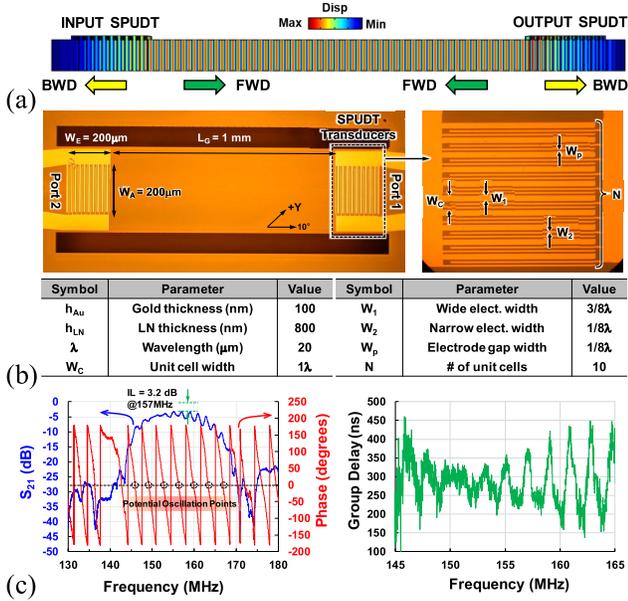


Fig. 2. (a) Cross-sectional mode shape of the SH₀ ADL with 10 SPUDT cells. The thickness of the cross-section is exaggerated. (b) Optical microscope images and key parameters of the fabricated ADL. (c) Open-loop measurement result of the SH₀ ADL with matching networks.

where Q_{eq} is the equivalent quality factor of the delay line. Therefore, a DL with large τ_G and high ω_o can be viewed as a high- Q element. The single-side band (SSB) bandpass response of the ADL can be modeled as a delay element with a selection filter in phase-space, given by

$$B(s) = e^{-s\tau_G} \cdot \frac{1}{1 + s\tau_B}, \quad (2)$$

where $s = j\Delta\omega$ is the offset frequency from the carrier in rad/s, $\tau_B = 2Q_{BW}/\omega_o$ is the time constant of the filter [9] and Q_{BW} is derived from the 3 dB bandwidth of the ADL [Fig. 1(a)]. Once the Barkhausen criterion is satisfied, the overall phase noise spectrum can then be derived by conventional linear time-invariant (LTI) analysis as,

$$L(\Delta\omega) \approx S_{PN} \cdot |H(j\Delta\omega)|^2 \cdot \left(1 + \frac{\omega_c}{\Delta\omega}\right) \quad (3)$$

and

$$S_{PN} = 10^{(-174 - P_c + IL + NF)/10} \quad (4)$$

$$H(j\Delta\omega) = \frac{1}{1 - B(s)} \Big|_{s \rightarrow j\Delta\omega} \quad (5)$$

where P_c is the carrier power in the loop in dBm, IL is the insertion loss of the ADL in dB, NF is the noise figure of the amplifier in dB, and ω_c is the corner frequency of $1/f^3$ phase noise in rad/s. It is apparent that *low IL* and *large delay* are the keys to obtain low phase noise. Fig. 1(b) shows the predicted phase noise of a 150 MHz ADL oscillator using (3) while assuming $P_c = 0$ dBm and an NF of 3 dB under various IL and delay conditions. Finally, the effective time delay in the oscillation loop is contributed by both τ_G and τ_B although the effect of τ_B is not significant in comparison with τ_G .

B. Design of ADL

Fig. 2(a) shows the 3D displacement plot of the ADL based on 3D finite element analysis in COMSOL. In this work, the ADL consist of an X-cut 800-nm suspended LiNbO₃ thin film and a 100-nm Au electrode to excite the SH₀ wave. The elastic wave propagation

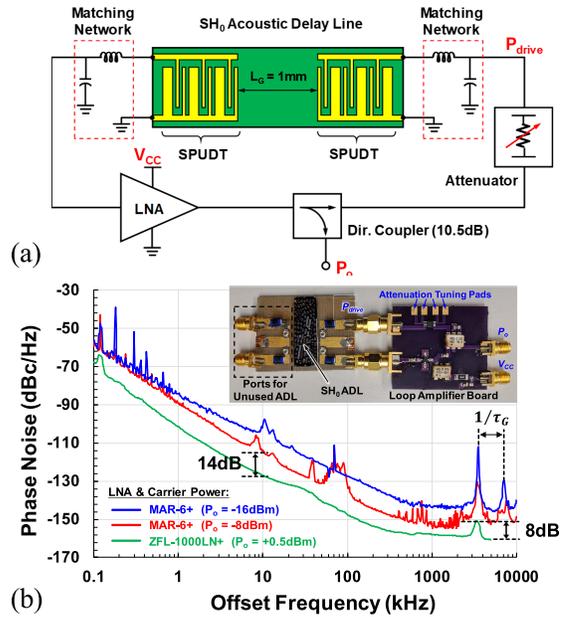


Fig. 3. (a) Circuit schematic of the ADL oscillator. (b) Measured phase noise spectrum under various carrier power levels. Inset: Oscillator board photo with MAR-6+ as the LNA.

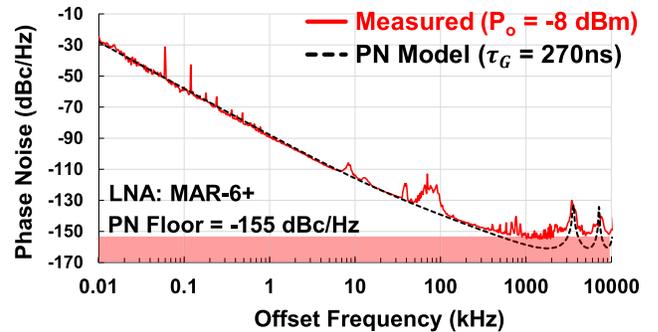


Fig. 4. Phase noise fitting for the ADL oscillator with $\tau_G = 270$ ns and $f_c = 15$ kHz.

direction is selected at -10° to the +Y crystallographic axis for maximizing the k^2 . As shown in Fig. 2(a), two sets of single-phase unidirectional transducers (SPUDT) are used to excite and receive the acoustic wave signal with minimal loss, where the detailed design procedure for SPUDT can be found in [6]. The central delay length is selected as $L_G = 1$ mm to yield a moderate $\tau_G = 275$ ns.

The optical images and the measured frequency spectra of the fabricated ADL are given in Fig. 2(b) and (c), respectively. The ADL is matched to 50 Ω ports using LC matching networks on the printed circuit board, showing a minimum IL of 3.2 dB at 157 MHz. We also observe that there are 7 potential oscillation points within ADL passband. With proper amplifier circuit design to meet Barkhausen condition at more than one frequency, multimode oscillation can be potentially sustained simultaneously [9]. The extracted group delay in Fig. 2(c) shows some ripples spanning from 200 to 400 ns, yielding an averaged τ_G around 275 ns. The in-band ripples in IL and τ_G are caused by the finite unidirectionality of the transducers used in these delay lines and internal multi-reflections [8].

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Oscillator Circuits

Fig. 3(a) shows the schematic of the oscillator circuit, which is composed of an SH₀ ADL, two impedance matching networks, a low

TABLE I
COMPARISON OF ADL-BASED RF OSCILLATORS

References	[10]	[12]	[13]	This work	
Material	GaN	GaN on Si	Quartz	LiNbO ₃	
Device Type	Delay Line Narrow Band	Delay Line Narrow Band	Delay Line Narrow Band	Delay Line Wide Band	
Acoustic Mode	A ₀ Lamb	SAW	SAW	SH ₀	
Frequency (MHz)	59.7	252	622	157	
DL Bandwidth (MHz)	–	~0.252* (0.1%)	1.3 (0.2%)	10 (6.45%)	
Insertion Loss (dB)	30.2	28.2	10	3.2	
Delay Time (ns)	–	–	–	270	
Power Supply Current, I _{CC} (mA)	40*	40*	65	16 (MAR-6+)	48 (ZFL-1000LN+)
Max. Output Power, P _{omax} (dBm)	15.1	5.2	13	-8**	0.5**
PN @1kHz (dBc/Hz)	-80	–	-109	-90	-101
PN @10kHz (dBc/Hz)	-120	–	-132	-114	-127
PN @300kHz (dBc/Hz)	-135	-105	-160	-148	-156

* Extracted from the Q-factor * The custom GaN amplifier used in [10] and [12] are the same
** Including the coupling loss of ~10 dB from the directional coupler

noise amplifier (LNA), a variable attenuator, and a directional coupler. Although several ADLs are designed on a single chip, in this work, a specific ADL is paired with two low noise amplifiers, namely MAR-6+ and ZFL-1000LN+ from Mini-Circuits, Inc., to evaluate the phase noise performance. They have with similar NF below 2.9 dB. The MAR-6+ is biased at $V_{CC} = 6$ V for lower carrier power operation, while ZFL-1000LN+ is operated at $V_{CC} = 15$ V to obtain larger carrier power. The variable attenuator is placed before ADL as a passive limiter to manually control the actuation power P_{drive} .

B. Experimental Results

Fig. 3(b) shows the measured phase noise spectrum of the ADL oscillators, with the picture of the evaluation board also provided in the inset. By changing the attenuation, three phase noise curves with different carrier power are recorded. The phase noise of -100 dBc/Hz, -114 dBc/Hz, and -127 dBc/Hz at the 10-kHz offset is measured under $P_o = -16$, -8 , and $+0.5$ dBm, respectively. The slope of these phase noise curves is -30 dB/decade, which may be caused by the $1/f$ noise from the piezoelectric material [14] as well as the amplifiers [15]. Using (3), the fitted phase spectrum is presented in Fig. 4 where $f_c = \omega_c/2\pi = 15$ kHz and $\tau_G = 270$ ns are used to produce the best-fit. We also noticed that the phase noise slope below 10-kHz becomes steeper as the output power increases from -16 dBm to -8 dBm. This effect is likely caused by the thermal nonlinearity of the delay line. On the other hand, higher carrier power leads to better phase noise at far-from-carrier offsets as expected, showing a minimum phase noise floor lower than -161 dBc/Hz.

Finally, we compare our work with published SAW ADL oscillators [12], [13] and Lamb wave ADL oscillators [10]. Thanks to the low IL in thin-film LiNbO₃ ADL, this work shows comparable phase noise performance to state-of-the-art ADL oscillators with preferable lower current consumption.

IV. CONCLUSION

This work presents the design and characterization of the first RF oscillators enabled by thin-film LiNbO₃ ADLs. The oscillators show phase noise of -114 dB/Hz at 10-kHz and -155 dBc/Hz at 1-MHz offset at a carrier frequency of 157 MHz. The measured performance is comparable to published SAW and Lamb wave ADL oscillators but with a 16 mA drive current. The LiNbO₃ ADL oscillators can be further improved by using longer delays and scaling up the oscillation frequency [16].

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