Surface Acoustic Wave Devices Printed at the Aerosol-Jet Resolution Limit

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This work was supported in part by the U.S. Department of Energy, Office of Nuclear Energy, Nuclear Energy Enabling Technologies (NEET) Program—Advanced Sensors and Instrumentation, and in part by the Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the Department of Energy under Contract DE-AC05-00OR22725.

ABSTRACT
Leveraging advances in additive manufacturing to implement radio frequency sensor technology has gained interest in recent years, motivated in part by the prospect of cost-effective, multi parameter sensing. Herein, aerosol-jet (AJ) printed surface acoustic wave (SAW) devices on LiNbO$_3$ with features at the resolution limit of AJ printing are reported. Compared to previously reported work, these devices demonstrate improved agreement between SAW designed and measured operating frequency at finer printed feature size, increased operating fundamental frequency, and are the first reported exploitation of harmonics of printed SAW sensor devices. Additionally, the application of printed SAWs as electrical resistance sensors and temperature sensors is demonstrated.

INDEX TERMS
Additive manufacturing, aerosol inkjet, printed sensors, surface acoustic wave (SAW).

I. INTRODUCTION
Printed radio frequency (RF) surface acoustic wave (SAW) sensor devices are a promising candidate technology for providing highly reconfigurable, cost effective, and multi-parameter sensing [1], [2]. SAW devices, widely used in the telecommunications industry as RF filters, function by coupling RF energy from an antenna or wired connection into a piezoelectric substrate’s surface oscillation, usually in the form of a Raleigh mode wave, through interdigitated transducer (IDT) electrodes deposited on the piezoelectric [3]. The $10^5$ reduction in RF SAW velocity compared to RF free space enables manipulation of RF energy in compact geometries (mm$^2$) to sense parameters including temperature [1], [4], stress/strain [5], electrical impedance [2], and gas concentrations [6].

The fundamental center operating frequency of a SAW device, $f_c$, is of high importance for SAW sensors because it determines the device RF operating regime. In general, SAW sensor sensitivity increases with increasing operating frequency [7], and device footprint decreases linearly with increasing $f_c$, highlighting the need for high frequency operation. In addition, the center frequency of a SAW device must be well determined by design for practical efficacy.

Although the precise value of $f_c$ depends on nuances of the IDT structure that affect internal IDT reflectivity such as electrode mass, electrode number, and electrode configuration, a good first order value can be determined by the piezoelectric substrate’s SAW velocity, $v_{SAW}$, and electrode period, $\Lambda_{IDT}$, as

$$f_c = \frac{v_{SAW}}{\Lambda_{IDT}}$$

The value of $\Lambda_{IDT}$ depends on the IDT electrode pitch ($p$) and IDT structure. Two commonly used SAW IDT structures are shown in Figure 1, along with a diagram of a SAW 2-port delay line device. For a “single electrode” or “2$p$” geometry as shown in Figure 1(b), the value of $\Lambda_{IDT}$ is

$$\Lambda_{IDT} = 2(a + g) = 2p$$

where $a$ is the IDT electrode width and $g$ is the gap between adjacent electrodes. For a “double electrode” or “4$p$” geometry as shown in Figure 1(c), $\Lambda_{IDT} = 4p$. The most widely available commercial aerosol-jet (AJ) printing tools are rated to achieve maximum resolution of conductor trace width ($a$) and spacing ($g$), of $\approx 10 \, \mu m$, corresponding to $\Lambda_{IDT}$ of $\approx 40$ and $\approx 80 \, \mu m$, for 2$p$ and 4$p$ type IDTs [8].

Regardless of the printing technology, fabrication of SAW devices with the highest achievable resolution is crucial for maximizing frequency of operation. Specifically, printed trace pitch, $p$, must be minimized for maximum $f_c$. 
Numerous emerging electronics printing methods are being investigated, with the highest resolution printed SAW devices reported to date being by electrohydrodynamic printing at 10 μm and 95.6 MHz \( f_c \) \[9\]. Granted that AJ printing is unable to match the resolution of other emerging methods \[10\], \[11\], it is of special interest for SAW based sensors due the versatility and relative maturity of AJ technology compared to other high-resolution printing options. However, most reported AJ SAW devices have feature sizes significantly larger than the AJ resolution limit of approximately 10 μm. This may be attributed to the significant fabrication challenges close to the resolution limit of AJ printing, most notably: linewidth control, overspray, and trace continuity.

Fig. 2 provides a survey of previously reported AJ printed SAW devices’ experimentally measured \( f_c \) versus \( v_{SAW}/\Lambda_{IDT} \), for devices demonstrated above 10 MHz, along with results from devices recently fabricated for this work. For this comparison, \( v_{SAW} \) was taken as the accepted room temperature values for the piezoelectric substrates used in each of the works. Cao et al. demonstrated an 18.5 MHz device with 50 μm electrode width and gap on 128° YX LiNbO\(_3\) substrate \[12\], and Vandormael et al. demonstrated an AJ printed device on lead zirconate titanate substrate with 20 μm electrode width and gap \[13\]. Both \[12\] and \[13\] demonstrated measured \( f_c \) in good agreement with the theoretical values based on (1), but at device features well above the 10 μm AJ lower limit. Morales-Rodriguez et al. demonstrated temperature sensing capability for a device with 20 μm IDT electrode width and gap, and also reported a variety of AJ printed SAW devices on 128° YX LiNbO\(_3\), up to 7 μm and 21 μm \( a \) and \( p \), respectively \[14\]. However, the AJ printed SAW devices reported by \[14\] exhibited large, nonmonotonic deviation from the expected relationship between \( f_c \) and \( \Lambda_{IDT} \), as shown in Fig. 1. It is expected that the measured value of \( f_c \) will differ from the prediction of (1) due to slight sample-to-sample variation in substrate \( v_{SAW} \), design details such as IDT electrode thickness, fabrication nonidealities such as surface contamination and overspray, and environmental parameters during experimental characterization (e.g. temperature). However, large unexplained deviations from expected frequency values raise concern that the nonidealities of AJ printing limit the ability to deterministically design and fabricate SAW sensors via AJ printing. To the contrary, the results presented herein indicate that despite the nonidealities of AJ printing, SAW sensors can indeed be deterministically designed to resonate at their expected \( f_c \), at trace width and trace gap features at as the resolution limit of AJ printing. Further, the ability to define AJ printed SAW performance characteristics beyond \( f_c \), to modulate SAW reflectivity by external passive loads, and to modulate the harmonics of \( f_c \) by temperature, are demonstrated herein, providing a path to multiparameter, RF sensor embodiments via AJ printing.

II. DEVICE FABRICATION AND CHARACTERIZATION

A series of SAW devices were designed with minimum features close to 10 μm, with both single and double electrode type IDTs. Double electrode IDTs were investigated for their expected superior harmonic generation efficiency, as well as lower short-circuit reflectivity \[3\], which is beneficial for modulation of IDT reflectivity by a passive electrical impedance \[2\]. Important device design parameters are summarized in Table 1 for the devices, which utilize a combination of single (2\( p \)) and double (4\( p \)) electrode type IDTs with IDT electrode period ranging from 128 μm to 36 μm. All devices fabricated for this work were printed on YZ-LiNbO\(_3\) (Roditi Corp., UK), for expected approximate IDT fundamental center frequencies ranging from 27 MHz to 97 MHz, given \( v_{SAW} \approx 3448 \) m/s.

Printing was performed with an AJ200 aerosol-jet system (Optomec, USA). Cllantair EXPT Prelect TPS 50 G2 Ag nanoparticle ink was aerosolized using ultrasonic atomization (Clariant, USA). A 100 μm diameter nozzle with approximate \( N_2 \) sheath and carrier gas flows of 29 and 21 sccm, respectively for Ag printed lines of approximately 9 to 10 μm width at a printing speed of 3 mm/s. All devices were aligned
to the printer stage for X-axis SAW propagation. The devices discussed in this work were diced to facilitate alignment prior to printing. Further general details of the AJ200 system and properties of the printed Ag ink can be found in [14].

Photomicrographs of devices described in Table 1 are shown in Fig. 3, with the device ID annotated in yellow, and the ports referenced in Table 1 labeled in dark green. The insets to the right of devices E-F show higher magnification of the IDT structures on Port 2 of these devices, with the trace width and pitch annotated. On devices E and F; the additional Port 3 IDT is also labeled; this port was un-probed for this work but is used as a reference reflector for time-domain analysis discussed in the subsequent section. All devices were probed with a calibrated RF microprobe with 50 µm signal/ground spacing, for which leads to the SAW devices were printed to accommodate. Devices E and F were also electrically connected to 50 Ω SMA connectors using Ag epoxy, to facilitate measurements of the circuits under varied Port 2 loads.

The transmission coefficient ($S_{21}$), is a measure of the voltage signal that will exit Port 2 relative to a voltage incident on Port 1 [15]. The frequency of the magnitude (dB) maximum of this measurement is the experimentally measured $f_c$ described by Fig. 1. The $S_{21}$ magnitude measurements for devices A-F are shown in Fig. 4. S-parameter measurements were performed with a TR1300/1 vector network analyzer (VNA) (Copper Mountain Technologies, USA). The peak locations for these devices displayed in Fig. 1 were found by smoothing the $S_{21}$ profiles with a zero-phase low-pass filter to remove ripple from the underlying $S_{21}$ curve (Python 3.7 SciPy 1.5.2 Signal). It is worth noting that SAW device IDTs can couple not only into surface modes of a piezoelectric substrate, but can also couple into bulk and shallow-bulk modes [3], resulting in multiple magnitude maxima when the devices are measured across a wide input frequency bandwidth. Peaks in $S_{21}$ that occur at frequencies that are not close to $f_c$ or not close to odd-integer multiples of $f_c$ are likely bulk, rather than surface, wave modes.

In addition to center frequency, the null bandwidth ($NBW$) of a SAW device is an important device design and performance parameter. The NBW determines the frequency range over which the device can operate, which must be determined by design for filters or for sensors employing schemes such as orthogonal frequency coding [5]. To demonstrate control over $NBW$, two SAW delay line devices with different numbers of electrode finger periods ($N_p$) and otherwise identical designs were fabricated (devices A and B). The $S_{21}$ magnitudes for these two devices are shown in Fig. 4, with annotations showing the approximate measured $NBW$. For the devices, with $N_p$ of 6.5 and 13.5, $NBW$ of 28 MHz and 15 MHz was observed. This is in good agreement with theoretical values for $NBW$. Using the approximation $NBW = 2f_c/N_p$ [3], the calculated $NBW$ is 30.8 and 14.8 MHz, for the devices with 6.5 and 13.5 electrode periods, respectively.

### TABLE 1. Selected AJ printed SAW device structure parameters.

| ID | $a$, µm | $p$, µm | Type | $N_p$ | Width |
|----|---------|---------|------|-------|-------|
|    | Ports 1,2 | Ports 1,2 | Ports 1,2 |  |  |
| A  | 9, 9 | 18,18 | $2p,2p$ | 13.5,13.5 | 890 |
| B  | 9, 9 | 18,18 | $2p,2p$ | 6.5,6.5 | 890 |
| C  | 9, 9 | 18,18 | $2p,2p$ | 14,14 | 890 |
| D  | 10,10 | 22,22 | $4p,4p$ | 16,16 | 720 |
| E  | 10,10 | 21,21 | $2p,2p$ | 27,27 | 1050 |
| F  | 10,10 | 21,32 | $2p,4p$ | 27,27 | 1050 |

**FIGURE 3.** Annotated photomicrographs of SAW devices A-F. The insets to the right show higher magnification of the IDT structures on Port 2 of these devices, with the trace width and pitch annotated.

**FIGURE 4.** $S_{21}$ responses for printed SAW 2 port structures from Table 1 and Fig. 3. $S_{21}$ local maxima occur near $f_c$, as predicted by (1) and are displayed in Fig. 2. $S_{21}$ is a measure of the fraction of RF power applied to the Port 1 IDT that is then transferred to Port 2.
FIGURE 5. Example of null bandwidth (NBW) control of SAW filters for two filters (A and B in Table 1). The two devices have the same structure other than number of IDT finger pairs and exhibit bandwidth expected proportionally to $N_p$, with values is close to the approximation $NBW = 2f_3/N_p$.

III. PRINTED SAW SENSOR RESPONSE: TEMPERATURE AND RESISTANCE

Demonstration of AJ printed SAW devices as sensors was performed for temperature and electrical resistance using devices D, E, and F. The temperature response of device D was evaluated at both its fundamental, $f_0$, and its 3$\text{rd}$ harmonic, $f_3 \approx 3f_0$. The temperature response was evaluated by measuring the wide band $S_{21}$ spectra while varying the temperature of device D between 18 and 34 °C and tracking the frequency shift of the local $f_0$ and $f_3$ peaks. An example wide band $S_{21}$ profile with annotations showing the locations of the $f_0$ and $f_3$ peaks is shown on the left-half of Fig. 6. The temperature was controlled by the RF microprobe stage and recorded by a thermocouple (TC) in contact with the device D substrate throughout the measurements. The right half of Fig. 6 shows the temperature values recorded from the TC along with the $f_0$ and $f_3$ values recorded for each measurement in the temperature sweep. The precise value of the observed $f_3$ peak is below $3 \times$ the observed $f_0$, likely due to the increased impact of second order effects on $f_3$ at higher frequency such as internal IDT reflectivity and variability in IDT pitch. After steady-state temperature was achieved at each of the five temperature values for which $S_{21}$ was recorded, 100 measurements of temperature and $S_{21}$ were performed. Each $S_{21}$ profile was low pass filtered using a zero-phase filter to remove noise using the Python SciPy Signal module prior to locating the $f_0$ and $f_3$ local maxima [16]. Measurements were not performed during transitions while the temperature of the stage was heating or cooling to relax requirements on timing synchronization between the TC and the SAW measurements.

The observed trend of decreasing peak frequency at both $f_0$ and $f_3$ is expected, since the temperature coefficient of frequency (TCF) for YZ-LiNbO$_3$ is known to be approximately $-94 \text{ ppm/°C}$ [3]. The TCF arises from the decrease in SAW propagation velocity with increased temperature and describes the fractional shift in frequency expected per degree temperature change. To compare the response of device D to accepted values for TCF, the observed TCF for these measurements were extracted from the device D $f_3$ data. The TCF was calculated from a linear fit to the experimental $f_3$ and TC data, where for a linear regression fit with slope $m$ and intercept $b$, the TCF is the ratio $m/b$ [17]. The Python SciPy Stats module [18] was used to perform the linear regression fit to the data, as shown in Fig. 7. The observed TCF for device D $f_3$ was $-95.9 \text{ ppm/°C}$, which is within $\approx 2\%$ of the accepted value for YZ-LiNbO$_3$. This level of agreement indicates that the observed $f_3$ resonance is indeed a surface mode. To the best of the authors’ knowledge, the 123 MHz operation of device D is the highest frequency reported operation of a SAW device in the literature reported to date.

The evaluation of printed AJ SAWs as electrical resistance sensors was performed by measuring the time-domain $S_{11}$ coefficient of devices E and F to varied resistive loads on Port 2 of these devices. The $S_{11}$ coefficient is a measure of the voltage signal reflected back to Port 1 relative to an incident voltage signal applied to Port 1. The time-domain measurements were performed with a center frequency of 85 MHz, a bandwidth of 35 MHz, and 6404 sweep points. The frequency-to-time conversion (inverse Fourier transform) was performed using the built-in functionality of the TR1300/1 VNA. The time-domain $S_{11}$ response was used to elucidate changes in the magnitudes of $S_{11}$ reflections returning to Port 1 at different times. The spatial location of Ports 2 and 3 on devices E and F are located at 6 and 3.5 mm from Port 1, corresponding to reflections that arrive centered at approximately 3.5 and 2 μs, respectively. The observed

FIGURE 6. The temperature response of device D. On the left, an example wide band $S_{21}$ measurement at a single temperature is shown with the $f_0$ and $f_3$ regions annotated. On the right, the peak frequencies for $f_0$ and $f_3$ throughout the temperature response test are shown, along with the temperature readout of the TC, vs measurement number.

FIGURE 7. Linear regression fit of the temperature recorded on the TC to the device D $f_3$ for the measurement data shown in Fig. 6. The observed TCF is in good agreement with the accepted TCF value for the substrate material, with a $\approx 2\%$ discrepancy.
S$_{11}$ peaks in time are in good agreement with the expected delay time of an incident signal, $\tau_d$, propagating to and from reflecting IDTs located at a distance $d$ from the input IDT (Port 1), based on Equation 3:

$$\tau_d = \frac{2d}{v_{S\text{AW}}}$$ (3)

The responses of devices E and F for resistive loads on Port 2 ranging from short to open are shown in Fig. 8. The variation in S$_{11}$ magnitude for both of these devices is concentrated at the expected 3.5 $\mu$s delay time, with negligible variation observed at the 2 $\mu$s location of the Port 3 reference peak, though some variation is also observed around 1.75 $\mu$s at $\tau_d/2$ due to parasitic electromagnetic coupling of the RF source to the Port 2 IDT electrodes, as well as after $\tau_d$, due to multiple reflection effects. The negligible variation of the Port 3 reflection located at 2 $\mu$s indicates that this reflection may be used as a reference pulse to compensate for varying parameters such as temperature or RF link strength.

The oppositely varying responses of devices E and F, where the device E Port 2 reflection magnitude decreases as a function of load resistance whereas device F Port 2 reflection magnitude increases as a function of load resistance, are intended features of their designed structures [3]. Device E utilizes 2p IDTs on both Port 1 and Port 2, which are known to show maximum reflectivity at short load condition, whereas device F was designed with a 4p IDT at Port 2, known to have the opposite reflectivity characteristic. Since achieving a 4p IDT at 85 MHz fundamental $f_c$ on YZ-LiNbO$_3$ requires IDT pitch well beyond the capability of AJ printing technology ($p \approx 10 \mu$m), the device F Port 2 IDT was implemented with a 4p IDT with its fundamental $f_c$ near 28 MHz, for a 3rd harmonic resonance near 85 MHz. The wide band reflection and transmission coefficients looking from Port 2 to Port 1, S$_{22}$ and S$_{12}$, respectively, for devices E and F are shown in Fig. 9 to demonstrate the asymmetric S-parameter character of device F. While device F exhibits an S$_{22}$ resonance near 28 MHz, negligible S$_{12}$ resonance is observed near 28 MHz on device F, as expected, since the Port 1 on this device has a fundamental $f_c \approx 85$ MHz. The S$_{22}$ and S$_{12}$ resonances observed at frequencies between 28 and 85 MHz, most prominently at 71 MHz, are most likely due to coupling of the device to bulk modes in the piezoelectric substrate. The demonstration of load resistance sensitivity for devices E and F are the first such demonstrations for printed SAW devices, and device F is the first reported demonstration of control over printed SAW performance characteristics beyond resonance frequency and bandwidth. These results indicate that despite the fabrication challenges inherent to printing SAW devices, fabrication of functionally complex SAW device designs is possible.

IV. CONCLUSION

A set of six SAW devices fabricated via AJ printing, printed at the resolution limit of AJ printing technology were presented. Compared to prior work on AJ printed SAW devices, the devices presented herein exhibited improved agreement between SAW designed and measured operating frequency at finer printed feature size, and increased operating fundamental frequency. The first reported exploitation of harmonics of printed SAW sensor devices as well as the first demonstration of printed SAWs as electrical resistance sensors was presented, indicating that traditional SAW device design strategies may be employed down to the feature size resolution limit of printing technologies. Although these results are promising, there are areas of fabrication of SAW by AJ printing that require further investigation. The authors note that the yield of printed device structures fabricated for this work was low and decreased with decreasing designed IDT pitch due to ink overspray. Additionally, the thickness of SAW IDT electrodes is an important parameter which has a strong effect on IDT reflectivity and harmonic efficiency, but AJ printing does not presently offer fine control over deposited
ink thickness (nm control). Future work which addresses the challenges of overspray and electrode thickness would be of high value for advancing the state of printed SAW technology.

ACKNOWLEDGEMENT

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