Impact of Noise on the Performance of Surface Acoustic Wave (SAW) Devices: A Review

Pratibha Yadav[1], Shashank Shekhar Jha[1*]

[1]*Department of Physics, Nalanda College, Biharsharif*
Nalanda – 803101, Bihar, India

***

Abstract - *Surface Acoustic Wave (SAW) devices are foundational components in modern telecommunications, precision sensing, and frequency control systems. While their compact size and high-frequency capabilities are highly advantageous, their overall performance is fundamentally constrained by inherent noise mechanisms. This review methodically examines the primary sources of noise in SAW devices, specifically thermal, flicker (1/f), and phase noises. We evaluate how these noise sources reduce critical device metrics such as the limit of detection (LOD) in sensors and the quality factor (Q) in oscillators. Furthermore, this review article highlights contemporary mitigation strategies, including material optimization, advanced interdigital transducer (IDT) design, and environmental compensation techniques.*

Key Words: Surface Acoustic Wave Device, Phase Noise, Flicker Noise, Quality Factor, SAW Sensors.

1. INTRODUCTION

Surface Acoustic Wave (SAW) technology has fundamentally transformed the scenery of modern electronics, establishing itself as a keystone in the fields of telecommunications, precision sensing, and frequency control. First mathematically described by Lord Rayleigh in 1885, surface acoustic waves are mechanical modes that propagate along the surface of a solid medium, with their energy decaying exponentially into the depth of the substrate [1]. In contemporary micro-devices, these waves are generated and detected using precisely patterned Interdigital Transducers (IDTs) deposited on high-quality single-crystal piezoelectric substrates, such as quartz, lithium niobate, or lithium tantalate. The inverse piezoelectric effect allows the input IDT to convert an alternating electromagnetic signal into a mechanical acoustic wave, while the direct piezoelectric effect at the output IDT reverses this process, enabling highly efficient, solid-state signal processing capabilities [2]. The passive nature, compact planar footprint, and ability to operate reliably at high frequencies—ranging from tens of megahertz up to several gigahertz—make SAW devices highly advantageous. Over the past few decades, they have become pervasive in radio frequency (RF) front-end modules for mobile communications, serving predominantly as bandpass filters, delay lines, and resonators. With the advent of 5G and the impending transition to 6G networks, alongside the exponential growth of the Internet of Things (IoT), the demand for ultra-miniaturized, high-performance acoustic wave devices has never been greater [3]. Furthermore, their extreme sensitivity to surface perturbations has spurred extensive development in the realm of physical, chemical, and biological sensors. In these applications, SAW devices are utilized to detect miniscule changes in mass loading, fluid viscosity, temperature, or external magnetic fields [4]. Despite these profound advantages and widespread applications, the operational boundaries and ultimate performance of SAW devices are strictly governed by intrinsic and extrinsic noise mechanisms. In any signal processing or sensing system, the Signal-to-Noise Ratio (SNR) is the definitive metric of efficacy. As device dimensions scale down to accommodate higher operational frequencies, and as the demand for precision increases, the detrimental effects of noise become increasingly pronounced. In sensor applications, the intrinsic noise floor directly dictates the limit of detection (LOD) and the overall resolution limits. Thermal (Johnson-Nyquist) noise and flicker (1/f) noise can easily mask the minute phase or frequency shifts induced by trace target analytes, rendering the sensor completely ineffective in critical, low-concentration environments [5]. Similarly, in communication systems, SAW resonators are frequently employed as the highly stable frequency-determining elements in feedback oscillators. In this context, internal device noise is upconverted into phase noise, manifesting as timing jitter in the time domain. Excessive phase noise severely compromises signal integrity, increases bit-error rates (BER) in digital transceivers, and causes destructive adjacent-channel interference in densely populated RF spectral bands [6]. Therefore, a comprehensive understanding of the physical origins and the phenomenological behaviour of noise in SAW structures is imperative for the advancement of next-generation acoustic technologies. This article systematically examines the primary sources of noise affecting SAW devices, with a specific focus on thermal fluctuations, flicker noise arising from material and surface defects, and the complex dynamics of phase noise in oscillator configurations. By bridging fundamental noise theory with practical device performance metrics, this paper evaluates how noise degrades critical parameters such as the quality factor (Q) and the LOD. Finally, we highlight contemporary and emerging mitigation strategies, encompassing advanced piezoelectric material optimization, innovative IDT architectures, and rigorous environmental compensation techniques, providing a clear roadmap for the development of ultra-low-noise SAW systems.

2. FUNDAMENTAL PRINCIPLES OF SAW DEVICES

A standard SAW device consists of a piezoelectric substrate (such as Quartz, Lithium Niobate, or Lithium Tantalate) patterned with metallic Interdigital Transducers (IDTs). When an alternating current (AC) voltage is applied to the input IDT, it induces mechanical strain, launching an acoustic wave across the substrate surface. The synchronous frequency of the generated wave is governed by the pitch (p) of the IDT fingers and the acoustic velocity (v) of the piezoelectric material. The central frequency (f_0) is expressed as:

$$f_0 = \frac{v}{\lambda} = \frac{v}{2p}$$

where λ is the acoustic wavelength.

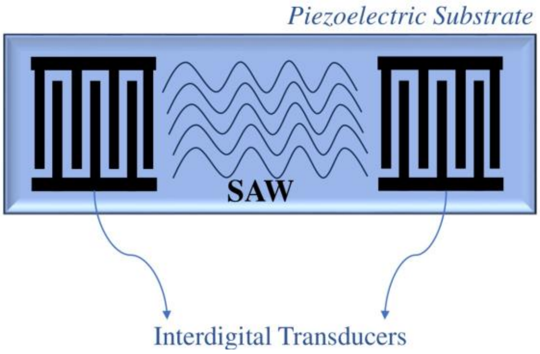

Fig -1: Schematic representation of a SAW delay line device

3. SOURCES OF NOISE IN SAW DEVICES

3.1 Thermal (Johnson-Nyquist) Noise

Thermal noise is a fundamental and irreducible electrical noise source present in all Surface Acoustic Wave (SAW) devices. It is generated by the spontaneous thermal movement of electrons within conductive materials and resistive circuit paths, regardless of whether an external voltage is applied. In SAW components, this effect is mainly linked to the metallic interdigital transducers (IDTs), electrode fingers, bus bars, contact pads, interconnections, and associated external circuitry. Because thermal agitation is an equilibrium phenomenon, it cannot be entirely removed and therefore defines the minimum background noise level achievable in practical SAW systems [7].

This noise mechanism is generally considered frequency independent over the normal operating range of SAW devices and is therefore treated as white noise. The root-mean-square (RMS) noise voltage can be expressed as:

$$V_n = \sqrt{4k_B T R \Delta f}$$

Where k_B is the Boltzmann constant, T is the absolute temperature, R is the equivalent resistance of the IDT, and Δf is the measurement bandwidth. In SAW devices, minimizing the series resistance of the IDT fingers is the primary method for reducing thermal noise.

In high-frequency SAW devices, the dimensions of the IDT electrodes are often reduced to achieve shorter acoustic wavelengths. However, narrower conductive paths can increase resistance and current crowding, thereby enhancing thermal noise contributions. Additional noise may also arise from packaging losses, wire bonds, connectors, and impedance-matching circuits [8]. These effects become especially important in wireless communication modules, oscillators, and precision sensing systems where low-noise operation is essential.

Several practical methods are used to limit thermal noise in SAW structures. One common approach is to lower the resistance of IDT electrodes by increasing metal thickness or selecting materials with superior conductivity. Electrode layouts can also be optimized to shorten current paths and reduce resistive losses. Improved impedance matching between the SAW device and surrounding circuitry helps minimize excess loss and maintain stronger output signals. In advanced systems, thermal stabilization techniques may be adopted to suppress temperature-dependent fluctuations [8].

Therefore, although thermal noise cannot be eliminated, careful electrical design and material optimization can substantially reduce its influence. Effective control of this noise source is important for improving sensitivity, frequency stability, dynamic range, and long-term reliability in modern SAW-based filters, resonators, and sensor technologies.

3.2 Flicker (1/f) Noise

Flicker noise, commonly referred to as 1/f noise, is a significant low-frequency noise mechanism observed in Surface Acoustic Wave (SAW) devices and is particularly critical in quartz-based SAW oscillators. Unlike thermal noise, which exhibits a flat spectral response, flicker noise increases as the frequency offset from the carrier decreases. For this reason, it often dominates the close-in phase noise region of high-stability oscillators and frequency control systems. The power spectral density of flicker noise can be represented as:

$$S_\emptyset(f) = \frac{h_{-1}}{f}$$

Where h_{-1} is an empirical constant dependent on the material and device geometry. In SAW devices, 1/f noise primarily originates from phonon scattering, material defects within the piezoelectric substrate, and surface impurities. Studies have shown that proper treatment and cleaning of the quartz surface can significantly reduce 1/f noise contributions [4].

In SAW devices, the physical origin of 1/f noise is more complex than that of thermal noise. It is generally associated with fluctuations in carrier mobility, trapping and detrapping processes at interfaces, lattice imperfections, grain boundaries in metallic electrodes, and defect states within the piezoelectric substrate. In quartz SAW resonators, microscopic surface contamination, adsorbed particles, and residual process-induced damage can further intensify these fluctuations [3]. Since acoustic waves in SAW structures are strongly confined to the surface region, any disturbance at or near the surface can directly modulate wave propagation and contribute to excess low-frequency noise.

Flicker noise has a direct impact on oscillator phase noise, short-term frequency stability, and sensor resolution. In communication systems, elevated close-in phase noise can degrade spectral purity and channel selectivity. In sensing applications, it may limit the detection of weak perturbations and small mass-loading effects. Therefore, minimizing 1/f noise is essential for advanced SAW resonators and oscillators used in navigation systems, wireless electronics, and precision instrumentation.

Several mitigation strategies have been reported. Careful substrate polishing, rigorous surface cleaning, contamination-free processing, and optimized electrode deposition can significantly reduce surface defect density and impurity-related fluctuations. High-quality quartz substrates with low dislocation density are also beneficial. In addition, improved packaging methods that isolate the device from moisture and airborne contaminants help preserve long-term low-noise performance [9,10].

Thus, flicker noise remains one of the principal factors limiting close-to-carrier performance in SAW oscillators, and continued progress in materials engineering and fabrication technology is essential for its suppression.

3.3 Phase Noise in SAW Oscillators

When a Surface Acoustic Wave (SAW) device is employed as the frequency-selective element in a feedback oscillator, the intrinsic electrical and material noise sources of the resonator are converted into **phase noise**, which appears as random short-term fluctuations in the phase of the generated output signal. In the frequency domain, phase noise is observed as spectral sidebands surrounding the carrier frequency and is commonly expressed as the single-sideband noise power density $\mathcal{L}(f_m)$ at an offset frequency f_m from the carrier. For SAW oscillators, the overall phase noise behavior is widely interpreted using **Leeson's model**, which relates oscillator noise performance to resonator quality factor, amplifier noise, signal power, and flicker-noise up conversion mechanisms [5].

$$\mathcal{L}(f_m) = 10 \log \left[\frac{1}{2} \left\{ 1 + \left(\frac{f_0}{2Qf_m} \right)^2 \right\} \left\{ 1 + \frac{f_c}{f_m} \right\} \frac{Fk_BT}{P_s} \right]$$

Where f_m is the offset frequency from the carrier, Q is the loaded quality factor, fc is the 1/f corner frequency, F is the noise figure of the amplifier, and P_s is the signal power.

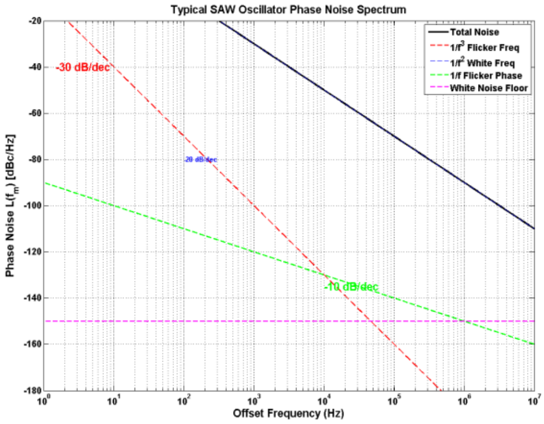

Fig -2: A typical phase noise spectrum $\mathcal{L}(f_m)$ vs. offset frequency f_m of a SAW oscillator, illustrating the $1/f^3$ flicker frequency noise, $1/f^2$ white frequency noise, 1/f flicker phase noise, and the flat white noise floor

In SAW oscillators, the loaded Q-factor plays a particularly important role because it determines how effectively the resonator suppresses phase perturbations near the carrier. Devices with higher Q values generally exhibit narrower resonance bandwidths and lower close-in phase noise. Quartz-based SAW resonators are often preferred for precision oscillators because of their excellent acoustic stability and relatively high-quality factors [11].

The close-to-carrier region is usually dominated by flicker noise translated through active devices, while thermal noise becomes more influential at larger offset frequencies. Additional contributions may arise from electrode resistance, substrate imperfections, packaging stress, temperature drift, and power-supply fluctuations. These effects can degrade oscillator spectral purity, timing accuracy, and communication performance.

To improve phase noise characteristics, designers typically use low-noise amplifiers, maximize resonator Q, optimize loop gain, increase output signal power within safe limits, and maintain stable thermal conditions. Careful layout, shielding, and clean bias circuitry also help suppress external interference. Therefore, phase noise analysis remains a central aspect in the development of high-performance SAW oscillators for wireless communication, navigation, and sensing applications.

4. IMPACT OF NOISE ON DEVICE PERFORMANCE

4.1 Degradation in Sensor Applications

Noise plays a decisive role in determining the sensitivity, accuracy, and long-term reliability of Surface Acoustic Wave (SAW)-based sensors. In gas sensors, biosensors, humidity sensors, and magnetic field sensing platforms, the target measurand modifies the propagation characteristics of the acoustic wave, typically producing a measurable shift in phase, delay, amplitude, or resonant frequency. The smallest detectable change is therefore strongly dependent on the background noise level of the device and associated readout electronics.

Phase noise and frequency fluctuations introduce uncertainty into the extracted sensing signal, especially when the induced frequency shift is very small. This limitation is commonly quantified through short-term frequency stability metrics such as Allan deviation or Allan variance, which are widely used for resonant sensing systems [12]. Elevated flicker noise at low offset frequencies is particularly harmful because many sensing events occur slowly and must be detected over longer averaging times. Similarly, thermal noise raises the broadband noise floor and reduces signal-to-noise ratio. As a consequence, weak responses caused by trace gas concentrations, low biomolecular mass loading, or small magnetic perturbations may become indistinguishable from random fluctuations.

In biosensing applications, this may lead to poor detection limits and reduced selectivity, while in environmental monitoring it can hinder the detection of hazardous gases at ppm or ppb levels. Therefore, minimizing noise is essential for achieving lower limits of detection (LOD), faster response times, and higher measurement confidence in advanced SAW sensor systems [6,8].

4.2 Degradation in Communication Systems

In wireless communication systems, SAW devices are extensively used as RF filters, duplexers, resonators, and oscillator components because of their compact size and excellent frequency selectivity. However, excessive noise—particularly phase noise—can significantly degrade communication quality. In oscillators, phase noise appears as random timing fluctuations or jitter in the time domain. This timing instability affects carrier synchronization, clock recovery, and modulation accuracy in digital transceivers.

High jitter levels increase bit error rate (BER), especially in high-speed data links employing advanced modulation formats such as QPSK, QAM, and OFDM. In addition, phase-noise sidebands spread energy into adjacent frequency channels, creating spectral regrowth and interference in crowded communication bands [4]. This issue is especially critical in modern cellular networks, satellite links, radar systems, and Internet-of-Things (IoT) devices where channel spacing is narrow and spectral efficiency is important.

Noise in SAW filters may also reduce out-of-band rejection and dynamic range, limiting receiver sensitivity. Consequently, low-noise SAW components are essential for reliable signal transmission, reduced interference, and stable operation in next-generation communication platforms.

5. MITIGATION STRATEGIES

Enhancing the Signal-to-Noise Ratio (SNR) in Surface Acoustic Wave (SAW) devices requires coordinated improvements in materials, fabrication processes, structural design, and environmental stability. Since noise in SAW components originates from multiple mechanisms—including thermal fluctuations, flicker noise, acoustic scattering, insertion loss, and temperature drift—no single solution is sufficient. Instead, a multi-parameter optimization strategy is necessary to obtain low-noise and high-performance devices for sensing, filtering, and oscillator applications.

5.1 Material Optimization

The choice of substrate material has a direct influence on acoustic propagation loss, electromechanical coupling, and intrinsic noise behaviour. High-purity single-crystal piezoelectric materials such as ST-cut quartz, lithium niobate ($LiNbO_3$), lithium tantalate ($LiTaO_3$), and langasite are widely used because of their superior crystallographic uniformity and stable acoustic properties [1]. Reducing impurities, dislocations, and lattice defects minimizes phonon scattering and internal energy dissipation, which in turn improves resonator quality factor and lowers excess noise.

Advanced substrate engineering has further expanded performance possibilities. Layered acoustic structures such as aluminium nitride (AlN) on sapphire, AlN on silicon carbide, and thin-film piezoelectric stacks provide enhanced acoustic confinement and reduced substrate leakage. These engineered platforms are especially attractive for high-frequency and low-loss SAW devices used in next-generation wireless systems [2].

5.2 Surface Treatment

Because SAW propagation is strongly confined to the near-surface region of the substrate, surface cleanliness and defect control are critical. Even nanoscale contamination, adsorbed moisture, organic residues, or polishing damage can disturb wave propagation and increase low-frequency flicker noise. Proper surface preparation has therefore become an essential step in device fabrication.

Processes such as UV-ozone cleaning, oxygen plasma treatment, wet chemical cleaning, and precision chemo-mechanical polishing are widely used to remove contaminants and reduce microscopic defects. Parker and related studies reported that careful surface conditioning can significantly suppress 1/f noise in quartz acoustic devices by reducing adsorption-related fluctuations and unstable defect states [13]. Surface passivation coatings may also help preserve long-term cleanliness and improve environmental durability.

5.3 Electrode Design

Because Interdigital transducer (IDT) geometry strongly affects insertion loss, acoustic reflections, impedance matching, and noise conversion. Poorly optimized electrodes can generate internal reflections, spurious bulk acoustic waves, and additional resistive losses, all of which degrade device performance.

Modern electrode configurations such as split-finger, double-electrode, floating-electrode, and apodized IDT designs are commonly employed to improve acoustic response and suppress unwanted modes [7,13]. Split-finger IDTs are particularly effective in reducing electrode reflection effects and minimizing triple-transit echoes. Increasing metallization quality and optimizing finger thickness also reduce series resistance, thereby lowering thermal noise. Improved electrode symmetry and current distribution further contribute to higher loaded Q-factor and better phase-noise performance in oscillator circuits.

5.4 Temperature Compensation

Temperature variation is a major source of frequency instability in SAW devices because acoustic velocity and elastic constants depend strongly on ambient temperature. Thermal drift not only shifts the operating frequency but may also amplify noise through fluctuating material parameters and stress effects.

To address this issue, Temperature-Compensated SAW (TC-SAW) devices have been developed using overlay layers such as silicon dioxide (SiO_2), silicon nitride, or composite thin films deposited on piezoelectric substrates [4]. These layers are engineered so that their temperature coefficient counteracts that of the substrate, thereby reducing net frequency drift. In precision applications, hermetic packaging, thermal shielding, and active temperature control circuits may also be employed.

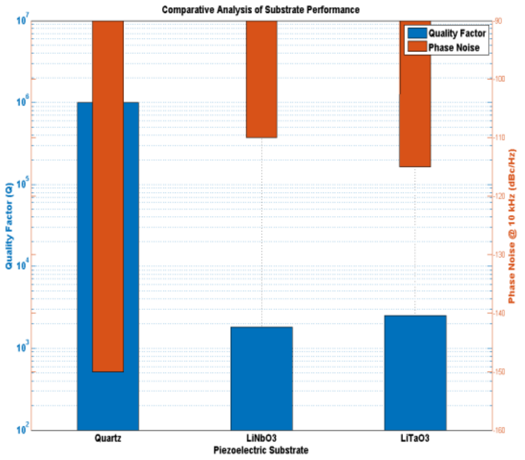

Fig -3: Comparative bar chart of Quality Factor (Q) and Phase Noise (at 10 kHz offset) across different piezoelectric substrates (Quartz, LiNbO3, LiTaO3).

5.5 Integrated Design Perspective

The most effective noise reduction is achieved when material quality, surface treatment, electrode geometry, and thermal compensation are optimized simultaneously. Such integrated strategies enable SAW devices with lower insertion loss, improved SNR, enhanced frequency stability, and longer operational lifetime. These advances are essential for high-resolution sensors, low-phase-noise oscillators, and compact RF front-end modules used in modern communication and industrial systems.

6. CONCLUSION

The ultimate performance limits of Surface Acoustic Wave (SAW) devices are strongly governed by the presence of intrinsic and extrinsic noise sources. Thermal noise establishes a fundamental lower boundary that is determined by operating temperature, electrical resistance, and measurement bandwidth, making it unavoidable in all practical systems. In contrast, phase noise and flicker (1/f) noise are highly dependent on material quality, fabrication precision, surface contamination, electrode conductivity, and resonator geometry. These controllable factors provide significant opportunities for engineering improvement.

The application of theoretical models, particularly Leeson's phase-noise framework, has enabled a deeper understanding of how resonator quality factor, amplifier characteristics, and signal power collectively influence oscillator stability. By optimizing interdigital transducer (IDT) dimensions, reducing electrode resistance, and enhancing acoustic confinement, researchers can substantially improve the loaded quality factor and suppress close-in noise. Likewise, advanced surface preparation methods, including precision polishing, plasma cleaning, and contamination-resistant passivation layers, have proven effective in minimizing defect-induced low-frequency fluctuations.

Future progress in SAW technology is expected to arise from the incorporation of advanced materials such as graphene, diamond-like carbon coatings, low-loss piezoelectric thin films, and high-conductivity nanostructured electrodes. In parallel, innovative acoustic waveguide architectures, phononic crystal structures, and temperature-compensated multilayer substrates may further reduce propagation loss and enhance frequency stability.

ACKNOWLEDGEMENT

The authors are thankful to Principal, Nalanda College, Biharsharif for providing technical support and space for pursuing this work.

REFERENCES

[1] A. Drafts, “Acoustic Wave Technology Sensors,” IEEE Transactions on Microwave Theory and Techniques, vol. 49(4), 2001, pp. 795-802.

[2] J. Kosinski and A. Ballato, “Measurements of acceleration-induced phase noise in surface acoustic wave devices,” Proceedings of the 44th Annual Symposium on Frequency Control, 1990, pp. 415-420.

[3] E. Rubiola and V. Giordano, “Advanced phase noise and amplitude noise of RF oscillators,” Review of Scientific Instruments, vol. 78(3), 2007, pp. 034703.

[4] T. E. Parker, “1/f phase noise in quartz s.a.w. devices,” Electronics Letters, vol. 15(10), 1979, pp. 296-298.

[5] D. B. Leeson, “A simple model of feedback oscillator noise spectrum,” *Proceedings of the IEEE*, vol. 54(2), 1966, pp. 329–330.

[6] P. Durdaut et. al., “Phase Noise of SAW Delay Line Magnetic Field Sensors,” *Sensors,* vol. 21(16), 2021, pp. 5631.

[7] D. Morgan, “*Surface Acoustic Wave Filters: With Applications to Electronic Communications and Signal Processing*,” 2nd ed., Academic Press, 2007.

[8] H. Nyquist, “Thermal agitation of electric charge in conductors,” *Physical Review*, vol. 32(1),1928, pp. 110–113.

[9] C. Campbell, *Surface Acoustic Wave Devices for Mobile and Wireless Communications*, Academic Press, 1998.

[10] K. Hashimoto, *Surface Acoustic Wave Devices in Telecommunications: Modelling and Simulation*, Springer, 2000.

[11] E. Rubiola, “*Phase Noise and Frequency Stability in Oscillators*,” Cambridge University Press, 2008.

[12] D. W. Allan, “Statistics of atomic frequency standards,” *Proceedings of the IEEE*, vol. 54(2), 1966, pp. 221–230.

[13] T. E. Parker, “Surface effects and flicker noise in quartz resonators,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 45(5), 1998, pp. 1233–1241.