# RF Power Handling of SAW Devices

## 1. Introduction

Increased signal power level is a key approach when good signal–to–noise ratio in RF transmission systems or outstanding noise floor in oscillator signals is required. While small size is one the key advantages of Surface Acoustic Wave (SAW) filters compared to competing technologies, the combination of high power levels and small size results in high power densities and therefore risk of premature failure for highly miniaturized solutions. Capabilities of Surface Acoustic Wave Devices to handle extended RF power levels are a frequent concern of system developers when choosing RF filter solutions.

This White Paper describes the capabilities and limitations of SAW technology with regards to higher RF power levels, explains power-related failure modes and associated life-time models, and outlines Vectron's capabilities to realize SAW component solutions with substantially increased power handling compared to standard SAW solutions.

While multiple parameters, such as filter design technique, center frequency of the device and applied signal wave form, influence power handling capabilities of SAW devices, recent technology improvements allow our products to reach life-time power levels of up to or slightly above 30 dBm for RF filters in the ≤2 GHz center frequency range. Due to the entirely compatible RF performance of standard and high-power technology realizations, high-power alternatives for existing standard technology SAW devices can be realized fast and technically straightforward.

## 2. Basic Functionality of SAW Devices

Surface Acoustic Wave (SAW) devices utilize the direct and inverse piezo-electric effect to convert an electrical radio frequency (RF) signal into a mechanical surface wave (and vice versa) through a structure called 'Inter-Digital Transducer' (IDT). This element consists of two interleaved comb-like metal electrode structures on the surface of a piezo-electric substrate material, realized by thin-film deposition and patterning technologies.

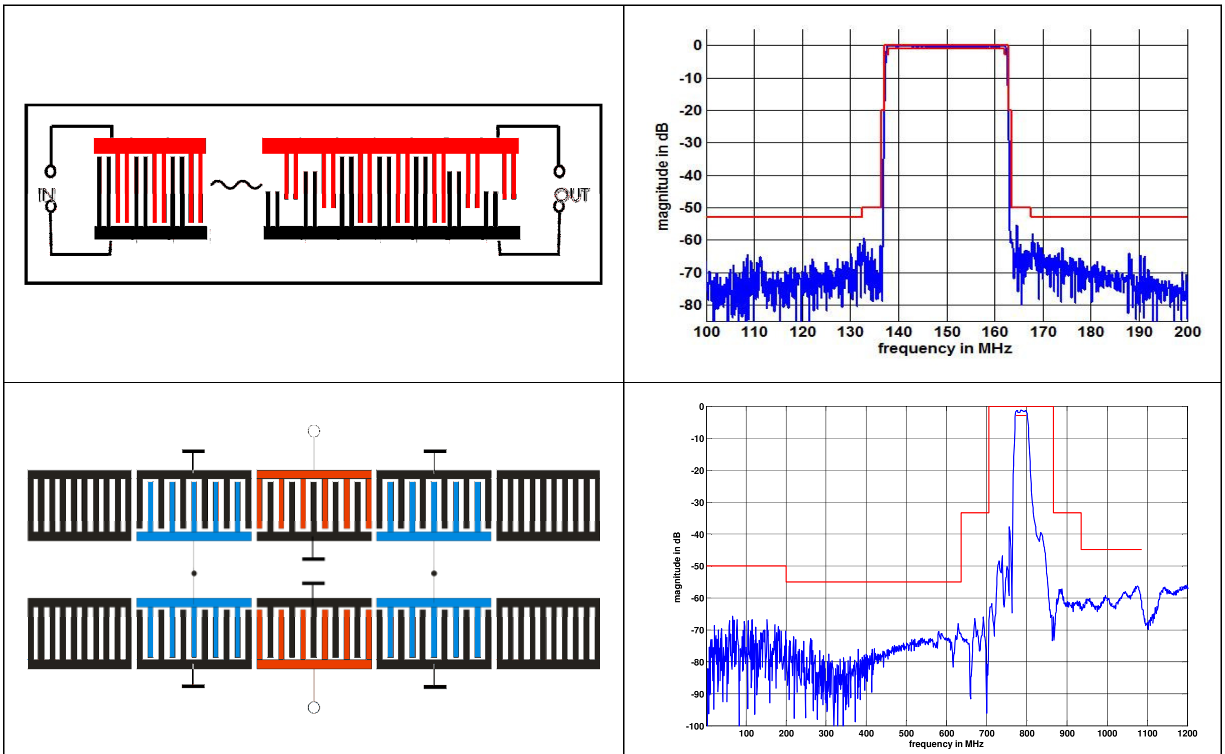


Figure 1: Schematic layout of a SAW transversal (top row) and resonator filter (bottom) with exemplary transfer characteristics.

The electrode systems, being placed with alternating electrical potential and typically constant periodicity, are able to generate and receive a mechanical surface wave at a specific resonance frequency, defined mainly by their periodicity and the characteristic phase velocity of the surface wave.
Schematic examples of two different realizations of this basic structure are shown in Figure 1, together with exemplary filter transfer functions.
The top row shows a 'transversal filter' design approach with an exemplary transfer function (normalized to minimum insertion attenuation level). This design technique allows for realization of extremely steep filter slopes, however, at the expense of insertion attenuation levels of (significantly) more than 10 dB. In this approach, the electrical transfer function can be understood as a cascade of the (reciprocal) electro-acoustic transfer functions of the two IDTs, since the signal is converted from electric to acoustic in the first IDT, travels along the surface into the second IDT and is converted back to an electric signal.
The bottom row in Figure 1 sketches the concept of a resonator filter technique, which strongly utilizes internal reflections of the SAW within the IDTs and in the reflector gratings left and right of the IDTs. As a result, resonant modes can be generated, which allow filter realizations with insertion attenuation levels of significantly less than 5 dB. While there are different ways to cascade several resonant modes electrically and/or acoustically, in all of the respective design approaches, standing wave patterns will occur as a result of forward- and backward-travelling waves due to the employed SAW reflector structures.
Resonator filter techniques show significantly higher power density levels within the acoustically active area, and are therefore more sensitive to high input power exposure than transversal filter design techniques, which do not strongly use internal reflections to cause resonant modes.

## 3. High-Power Damage Modes of SAW Devices

Under the resonance condition described above, a distinct standing wave pattern occurs in the resonator structure. With increasing power level of the applied RF signal, the amplitude of the SAW increases, eventually resulting in damage in the electrodes' material system at defined positions with high micro-acoustic stress. The typical damage phenomenon is frequently referred to as 'acousto-migration' and is caused by mobility of electrode material along microscopic grain boundaries in the metal system, causing extrusions from and voids within the electrode fingers.
Figure 2 shows Scanning Electron Microscope (SEM) images of IDT electrodes without application of high power (left) and a typical pattern of acousto-migration after excessive high-power exposure showing severe extrusions close to the point of causing short circuits between adjacent fingers of opposite polarity (center). Signs of this effect will occur in any resonant SAW device upon exposure to high power for an extended period, and eventually also in non-resonant devices at even higher power density levels. Upon excessive increase of the input power (e.g. >40 dBm), the high power density will eventually result in melting and evaporating electrode material or even mechanical cracks or melting of the piezo-electric single-crystal substrate, as shown in Figure 2 (right).

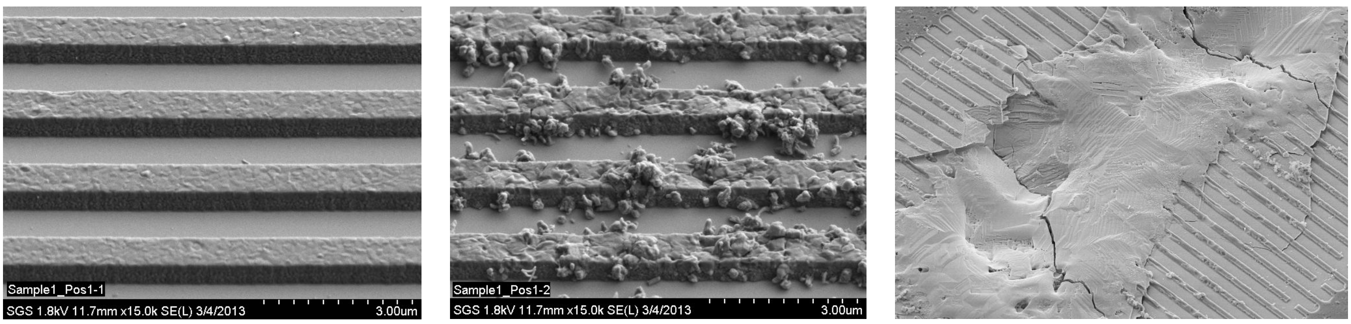


Figure 2: SEM images of IDT structure 'as manufactured' (left), damaged by continuous acousto-migration due to excessive high-power exposure (center) and damaged by catastrophic event (right).

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It is important to note that the failure mode acousto-migration can be considered a cumulative effect, whereas any massive damage as shown in Figure 2 (right) cannot be described well with a cumulative lifetime model, but is characterized by reaching a threshold of allowable electrical field between adjacent electrodes, defined by breakthrough field thresholds of piezo-electric substrate and/or atmosphere within the SAW device's package.
The time-to-failure, i.e. the life-time of a device at the tested power level, is in general determined by a highly accelerated test procedure using much higher power than eventually to be specified, in order to drive the device into a defined failure criterion, which is typically a certain increase of insertion attenuation or reduction of bandwidth.
Figure 3 shows an example for long-term test data of a SAW RF filter degrading in a high power test, eventually resulting in increased insertion attenuation and reduced bandwidth (left), as well as the result of the iterative evaluation of the filter bandwidth (right).

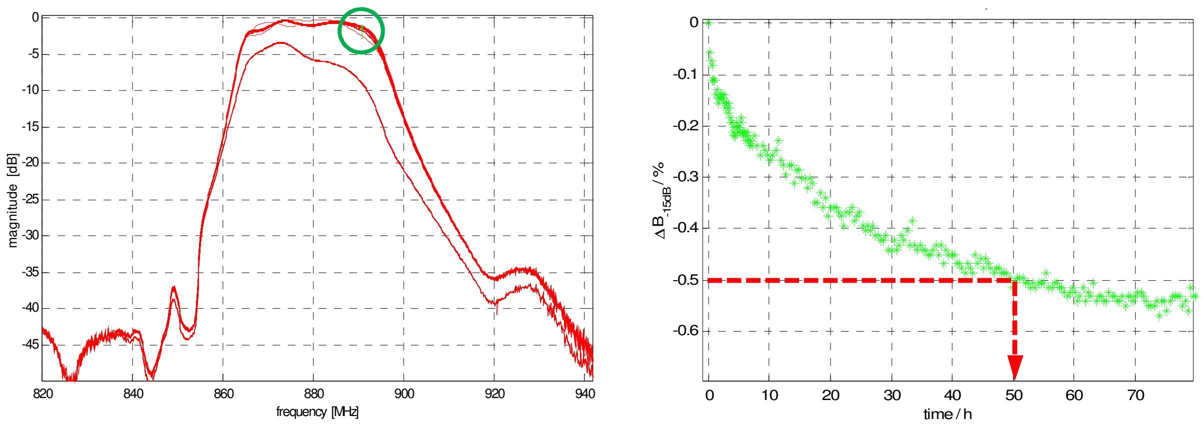


Figure 3: Typical performance degradation of SAW RF filter in high-power test and corresponding structure damage.

Throughout the test, the device is repeatedly exposed to a narrow-band continuous wave signal at its worst-case frequency (encircled green lines at ~890 MHz in left image) for an extended period, followed by a fast measurement of the filter characteristic, which is used for evaluating the damage progress (red curves).
The time to reach the defined failure criterion for the device, i.e. the time-to-failure, is determined by repeated evaluation of the device's characteristic throughout the test progress, i.e. typically $S_{21}$. In this example, applying a 0.5 % reduction of the -15 dB-bandwidth as failure criterion, the time-to-failure will amount to 50 h, as shown in Figure 3 (right).

It is important to note that power levels specified in Vectron datasheets consider – unless specified differently – worst-case conditions, i.e.

- continuous wave exposure,
- 15 years of life-time,
- exposure frequency position with highest sensitivity (fastest damage),
- maximum operating temperature,

and therefore cover all possible applications – within the limits of the datasheet – the device can be exposed to.
While different exposure frequencies within the pass-band typically result in somewhat different progress of damage, out-of-band, i.e. stop-band power handling capabilities are generally higher than in-band power handling. As briefly explained in section 2, SAW devices consist of inter-digital structures converting electrical to mechanical energy with a frequency-selective characteristic.

Hence, applying a signal with a frequency significantly away from the IDT's resonance frequency, the IDT mainly acts as a capacitor only, i.e. very little mechanical energy is transmitted, which is the root cause for the considered acousto-migration.
For very high out-of-band power levels, a typical limitation is therefore less determined by cumulative acousto-migration effects, but by the maximum permissible electrical fields between the electrodes of the interdigital transducers. Extending these physical limits will result in failure modes such as shown in Figure 2 (right).
As one typical example, filters used in the frontend of the receive branch of frequency division multiple access (FDMA) systems will see very little in-band power, whereas a potentially leaking high-power transmit signal will affect the receive filter in the stop-band only, as illustrated for a LTE band 5 filter in Figure 4.

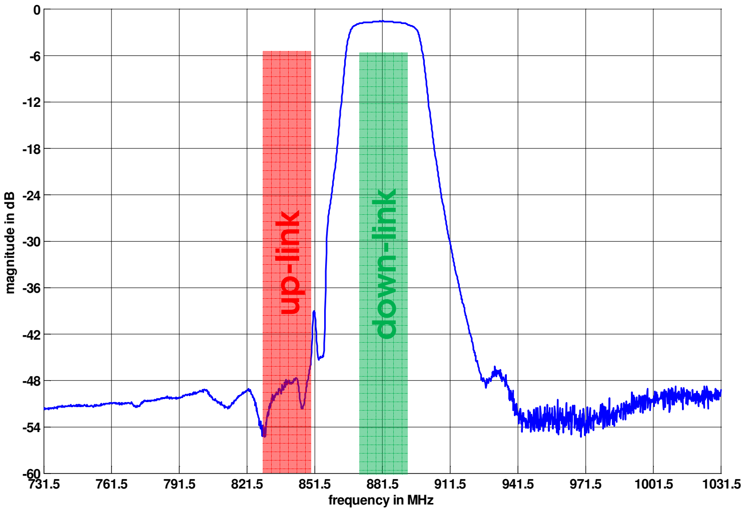


Figure 4: Exemplary signal power application in pass-band (red) vs. stop-band (green).

Additionally, narrow-band signals, e.g. using a SAW filter in the clean-up stage of a crystal oscillator, will typically result in faster damage than signals with a wider spectrum, such as e.g. CDMA or LTE signals having a comparable total signal power, related to the more pronounced power density distribution within the SAW structure.

## 4. Lifetime Model for SAW Devices

The time-to-failure for a SAW device can be described mathematically in a simple lifetime model, together with design-specific parameters, applied input power and ambient temperature.
In general, the continuous and cumulative failure mode acousto-migration can be sufficiently well described by the following equation:

$$TTF = C \cdot P_{in}^{-m} \cdot e^{\frac{W_0}{k\vartheta}},$$

with

| | | |
|---|---|---|
| $TTF$ | - | time to failure (within which device can be operated with cont. wave power), |
| $C$ | - | design- and material-specific constant, |
| $P_{in}$ | - | input power, |
| $m$ | - | acceleration factor, |
| $W_0$ | - | activation energy, |
| $k$ | - | Boltzmann's constant, |
| $\vartheta$ | - | ambient temperature. |

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The model can be considered cumulative, i.e. periods with different power levels and/or device temperature contribute to the total life-time as follows:

$$TTF_{total} = \sum_i T_i = C \cdot \sum_i P_i^{-m} \cdot e^{\frac{W_0}{k\vartheta_i}}$$

However, under most real-world scenarios, periods with the highest applied power will mainly determine the life-time of the device due to the exponential dependence of this term on the input power level.
As an additional consequence, signals applied with a certain duty cycle will prolong the life-time of the device tested with respect to continuous-wave exposure proportionally.

Test results for time-to-failure obtained at various power levels are plotted into a double-logarithmic chart to determine the power acceleration factor applicable for extrapolation to determine the device's maximum life-time exposure.
Naturally, the power range suitable for testing is limited by electrical break-through for high and exponentially increasing test time requirements for low power levels.
Figure 5 shows measurement results at several power levels (25…30 dBm) for a reference design (standard technology) at 820 MHz with the corresponding time-to-failure.

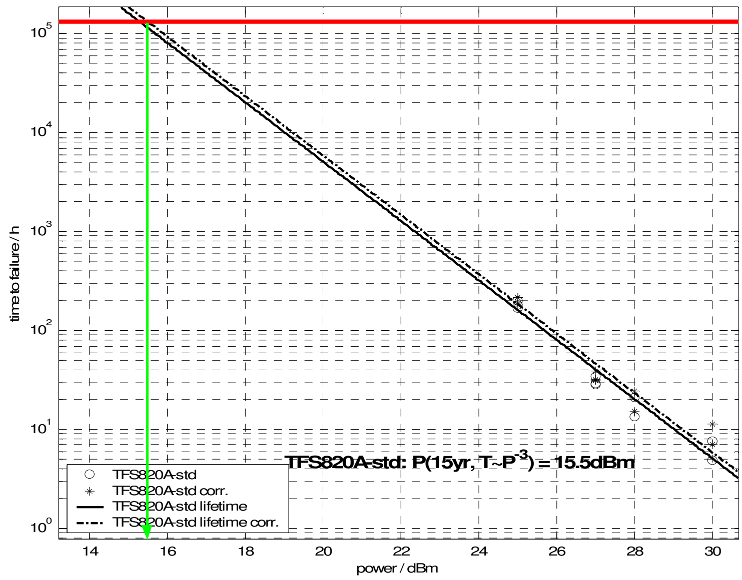


Figure 5: Lifetime model for reference filter design at 820 MHz.

Interpolation of the measurement values suggests a power acceleration factor $m \approx 3$, i.e. $TTF \approx C \cdot P_{in}^{-3} \cdot e^{\frac{W_0}{k\vartheta}}$, which is obtained as a good approximation for many SAW designs. Extrapolating this line until its intersection with the desired life-time of 15 years (red line, green arrow) suggests a maximum power exposure over life-time of approximately 15.5 dBm for this device.
While the solid black line and the circles show the actual measurement result, the dashed black line and the asterisks denote the values corrected by the power-related self-heating of the device, which can be evaluated from characteristic temperature-related frequency shifts at the start of the test.
The 'Arrhenius term' describing the dependence of device degradation on ambient temperature or a temperature change related to energy dissipated within the SAW device at high power levels can be approximated by $e^{\frac{W_0}{k\vartheta}} \approx c_1 \cdot 2^{-\frac{\vartheta}{10K}}$, which – for this example – simplifies the life-time model to

$$TTF \approx C \cdot c_1 \cdot P_{in}^{-3} \cdot 2^{-\frac{\vartheta}{10K}} .$$

Therefore, the following rules of thumb can be applied:

$\Delta\vartheta$ = +10 K $\Leftrightarrow$ $\Delta TTF$ = -50 %
$\Delta\vartheta$ = +10 K $\Leftrightarrow$ $\Delta P_{in} \approx$ -1 dB
$\Delta P_{in}$ = +1 dB $\Leftrightarrow$ $\Delta TTF \approx$ -50 %

Figure 6 shows the effect of different device temperatures, including ambient temperature and temperature increase due to power dissipation, to the expected time-to-failure and life-time power handling capabilities of the example at 820 MHz.

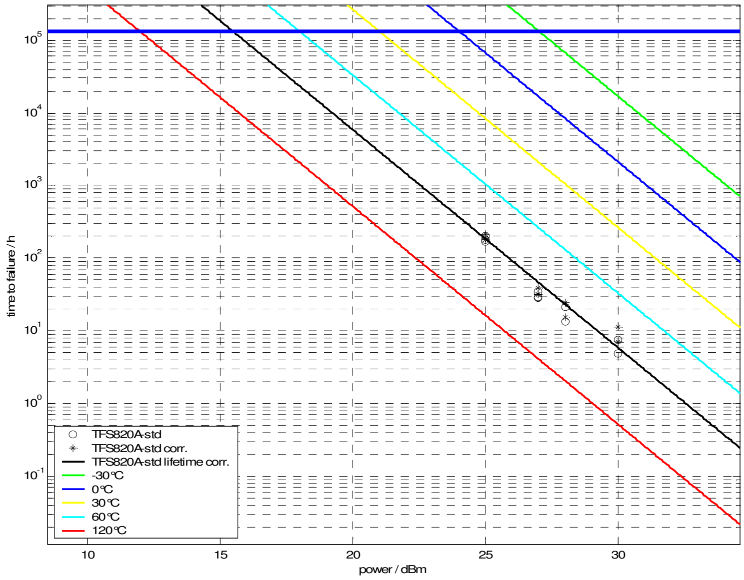


Figure 6: Temperature dependence of time-to-failure and life-time power level related to device temperature (actual test temperature (black): 85 °C).

Due to the significant influence of travelling and standing wave patterns within the micro-acoustic structure, the typical power levels for SAW devices differ strongly for different design approaches. Figure 7 shows a conservative estimation for typical power levels achievable for different SAW design techniques, assuming continuous-wave exposure at worst-case frequency within the pass-band and at maximum operating temperature (typ. 85 °C). Exemplary filter characteristics are shown for each power level line.

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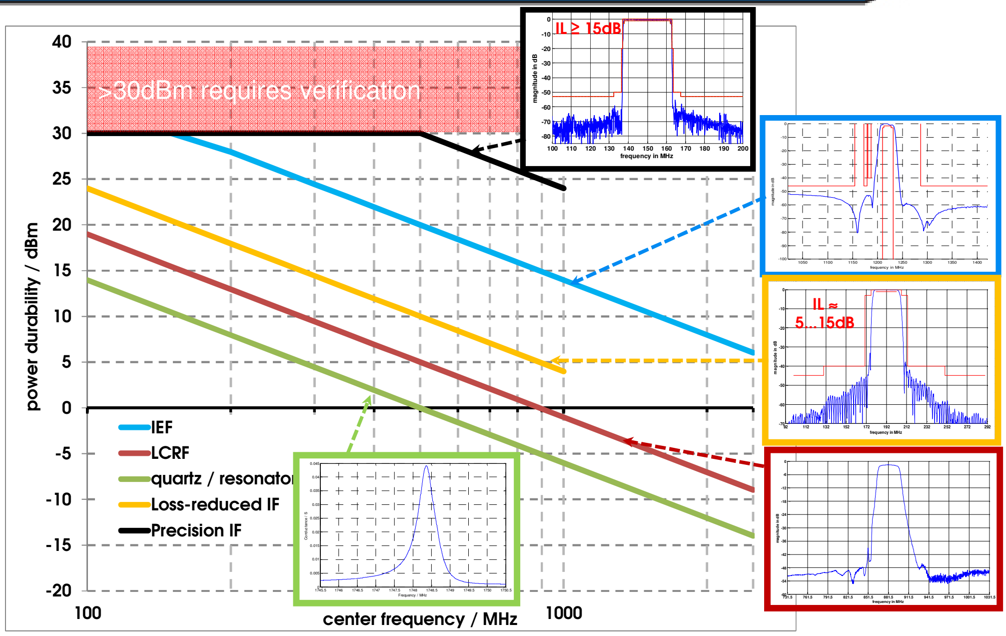


Figure 7: Typical life-time power exposure levels for different SAW design approaches (standard technology).

## 5. High-Power SAW Technology

Figure 5 and Figure 7 in section 4 show typical power levels achievable for SAW devices realized in Vectron's standard technology. In this technology, the electrodes mainly consist of aluminum, and show a comparatively high tendency for acousto-migration, i.e. material mobility along grain boundaries under high power exposure.

Optimization of the electrode metallization system now allows for significantly higher stability of the material system, which enables realization of SAW devices with substantially improved power durability.

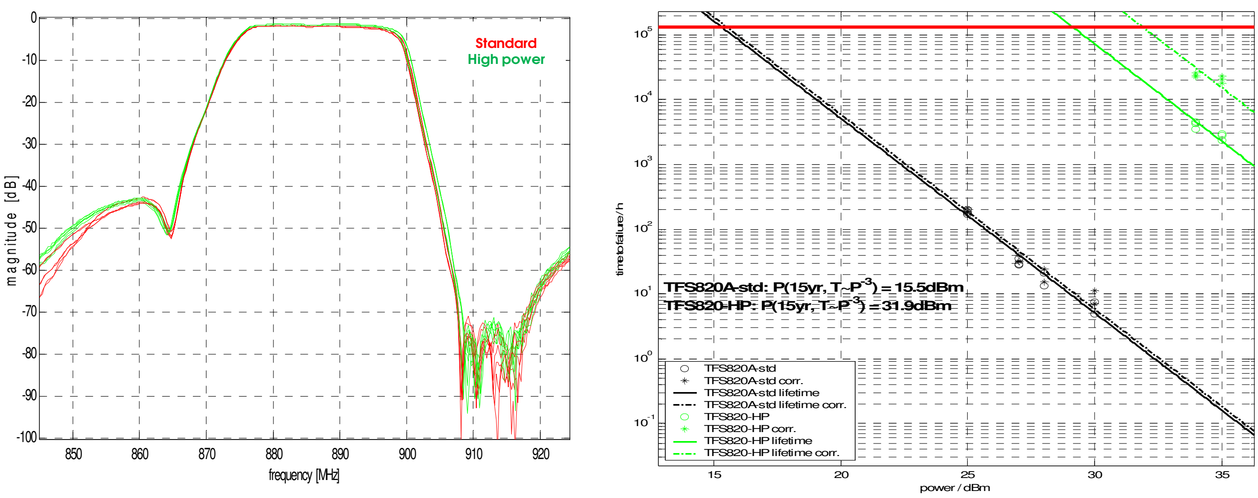


Figure 8: Device characteristics and power testing results for 820 MHz reference device (TFS820A) in standard and high-power electrode technology.

A typical comparison of device characteristics and power test results for standard and high-power electrode systems is shown in Figure 8. The left comparison underlines the complete equivalence of the RF characteristics of devices realized in the two compared technologies. Thanks to this fact, high-power

alternatives for existing standard technology SAW devices can be realized fast and technically straightforward.
While the black results in Figure 8 (right) show power test results for our standard technology, the high-power solution, reflected in the green data points, shows approx. 15 dB higher power handling capabilities. The result considers power-induced self-heating (dashed lines) due to the substantially higher power level required to reach the cut-off criterion in 'acceptable' test time. The significant offset between green solid and dashed lines results from higher device temperature due to much higher applied power, i.e. up to 35 dBm compared to ≤30 dBm for the more sensitive standard technology.

Scanning electron microscopy images of comparable test parts are shown in Figure 9, whereas the high-power version was exposed to significantly higher power for much longer time.
While the left image, showing the standard technology part, indicates strong acousto-migration, voids and extrusions in the metallization, the right image, i.e. the high-power solution, only shows minimal signs of this degradation. Despite the massive difference in applied ultrasonic energy between right and left structure, the much lower damage underlines the effective reduction of acousto-migration.

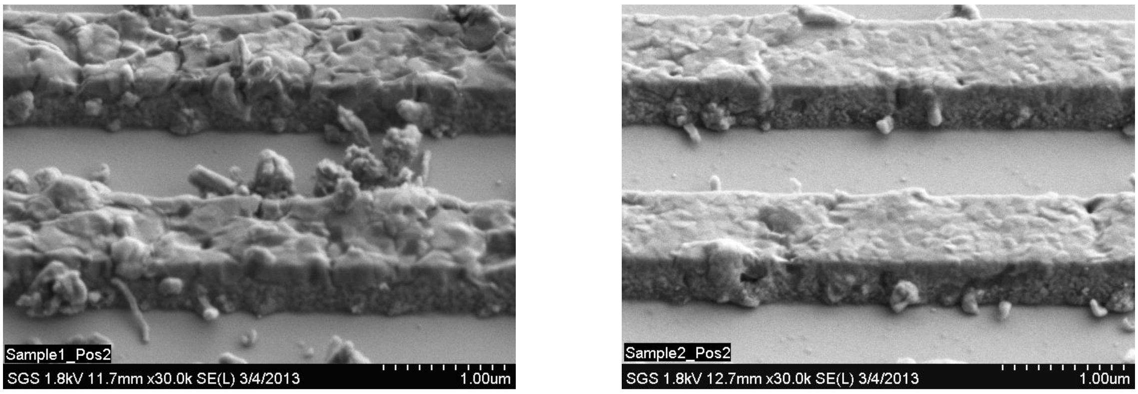


Figure 9: SEM images of acousto-migration pattern for a 900 MHz test structure for standard (0.5 h at 30 dBm, left) and high-power electrode system (190 h at 34 dBm, right).

A conservative estimation for achievable life-time power levels for Vectron's high-power SAW technology, depending on different design techniques, is shown in Figure 10.
A minimum of 10 dB improvement in power handling capabilities under comparable conditions, i.e. exposure frequency, temperature and duty cycle, is achieved by utilizing our high-power technology compared to a standard solution.
Still, for very challenging power handling specifications, we consider individual, design-specific characterization mandatory, also due to electrical field levels potentially reaching >>1 V/µm and therefore increasing risk of severe device damage due to electric flash-over.

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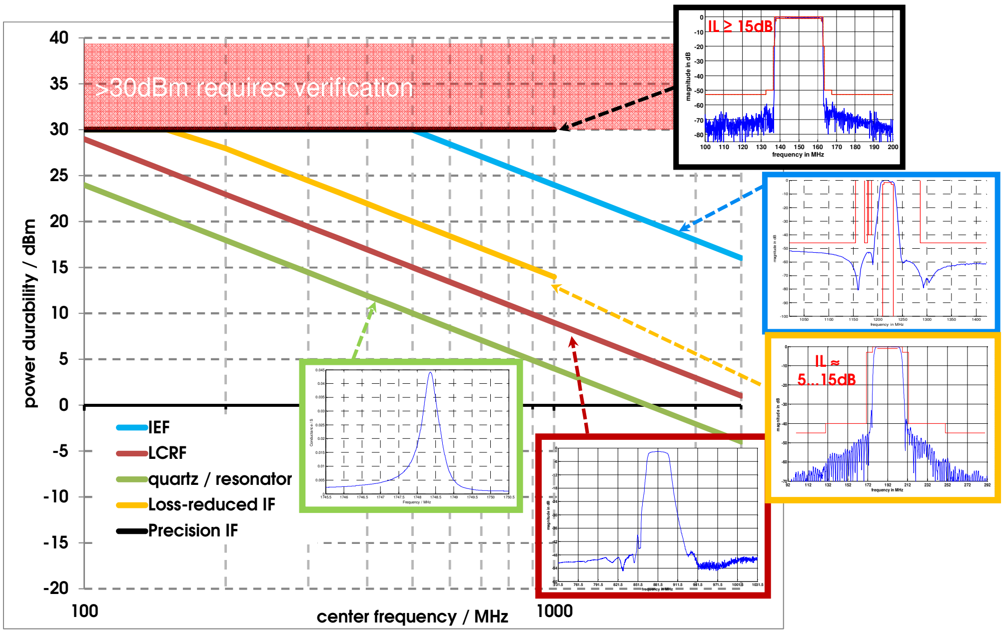


Figure 10: Typical life-time power exposure levels for high-power technology for different SAW design approaches.

Additional to the technological improvements described above, certain design approaches can be applied to reduce power density levels within the SAW structures, which are essentially insignificant in terms of RF performance. Basically, these approaches consist of cascading several resonant SAW structures. By this, the RF current is distributed over different branches and the voltage drop is cascaded over various resonant structures.

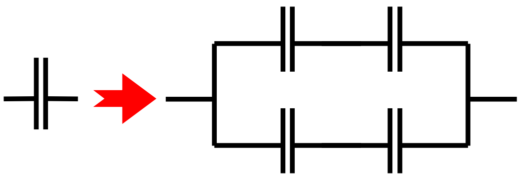

Figure 11: Simplified view of SAW structure cascading principle to reduce power density.

Grossly simplified and using a single capacitance as an equivalent circuit for a SAW resonator, Figure 11 shows the underlying principle. Replacing a single resonator by a cascade of '$N{\cdot}N$' SAW structures will therefore reduce power density levels by $10 \log N^2$, e.g. by 6 dB for $N=2$.

## 6. Conclusion

Vectron developed a highly effective method to significantly reduce the main failure mode degrading SAW filter performance under high power exposure. Utilizing our new high-power SAW process technology and appropriate filter design approaches, low-loss RF SAW filters can now be realized reaching power levels up to or slightly above 30 dBm under all application conditions and over life-time.

This new technology is fully qualified and available for new designs as well as for realization of high-power versions of conventional designs in our existing product portfolio.

Author / contact information:

Richard Gruenwald
Director Engineering
Vectron International GmbH
rgruenwald@vectron.com

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