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SAW RFID devices using connected IDTs as an alternative to conventional reflectors for harsh environments

Cécile Floer, *Student Member, IEEE*, Sami Hage-Ali, *Member, IEEE*, Pascal Nicolay, *Senior Member, IEEE*, Hugo Chambon, Sergei Zhgoon, *Senior Member, IEEE*, Alexander Shvetsov, Jérémy Streque, Hamid M'Jahed, and Omar Elmazria, *Senior Member, IEEE*

***Abstract*—Remote interrogation of surface acoustic wave ID-tags imposes a high signal amplitude which is related to a high coupling coefficient value (K^2) and low propagation losses (α). In this paper, we propose and discuss an alternative configuration to the standard one. Here, we replaced the conventional configuration, i.e. one interdigital transducer (IDT) and several reflectors, by a series of electrically connected IDTs. The goal is to increase the amplitude of the detected signal using direct transmission between IDTs instead of the reflection from passive reflectors. This concept can therefore increase the interrogation scope of ID-tags made on conventional substrate with high K^2 value. Moreover, it can also be extended to suitable substrates for harsh environments such as high temperature environments: the materials used exhibit limited performances (low K^2 value and relatively high propagation losses) and are therefore rarely used for identification applications. The concept was first tested and validated using the lithium niobate 128°Y-X cut substrate, which is commonly used in ID-tags. A good agreement between experimental and numerical results was obtained for the promising concept of connected IDTs. The interesting features of the structure were also validated using a langasite substrate, which is well-known to operate at very high temperatures. Performances of both substrates (lithium niobate and langasite) were tested with an in-situ RF characterization up to 600°C. Unexpected results regarding the resilience of devices based on congruent lithium niobate were obtained.**

***Index Terms*—high temperature, lithium niobate, radio frequency identification (RFID), surface acoustic wave (SAW)**

I. Introduction

THIS paper is an extended version of the conference paper [1] presented at the 2019 Joint Conference of the International Frequency Control Symposium and the European Frequency and Time Forum in Orlando, USA.

In modern society, the remote sensing of physical parameters becomes essential, as well as the remote identification of the sensors, especially for tracking applications. Standard RFID technology is based on silicon integrated circuit (IC tags), which can be interrogated over large distances. These devices already have numerous applications in logistics and production lines monitoring. One of the major limitations of this technology is the need of initial RF power conversion to DC power, to read the devices [2]. Surface acoustic wave (SAW) ID-tags (like in Fig. 1) are another solution. The growing trend of the SAW market, and more precisely of the coding principle, was already mentioned twenty years ago [3,4]. SAW devices have the advantage of being totally passive. Moreover, these devices consist only of a piezoelectric substrate with metallic IDTs on top of it. The reverse and direct piezoelectric effects are used to convert electromagnetic signals into surface acoustic waves, and vice versa. External parameters such as temperature [5], strain or the presence of gas can disturb the wave propagation. Thus, the position of the echoes and their sequence can be used to sense external parameters and to identify the responding sensor [6].

For SAW RFID applications, substrates with a high coupling coefficient (K^2) and low propagation losses (α) are required due to their direct influence on the amplitude of the detected signal. The higher the amplitude of the echoes, the longer the interrogation distance. In order to increase the performances of ID-tags, the use of optimized designs is needed.

In this paper, we study a structure based on connected IDTs (see Fig. 2). The main advantage in such a structure is to have a direct transmission between the IDTs, as opposed to a reflection from passive reflectors in traditional ID-tags. To the best of our knowledge, a similar configuration with connected IDTs has already been mentioned in [6] but has never been used experimentally for an ID-tag application. This configuration may be a particular case of the SITO structure mentioned in [7], which has not been studied experimentally.

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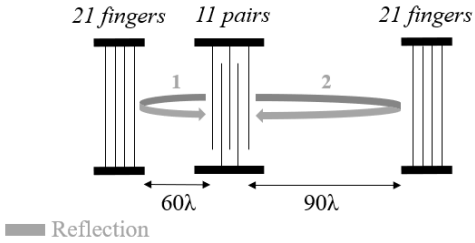

Fig. 1. First configuration (device #1), with one IDT and two reflectors (conventional ID-tag configuration).

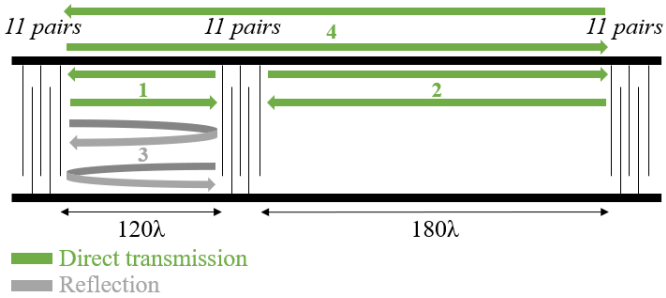

Fig. 2. Second configuration (device #2), with three electrically connected IDTs.

The main goal here is to improve the level of the detected peaks for ID-tags applications using connected IDTs.

The use in a hostile environment usually degrades the performances of the devices and therefore the quality of the collected signal. This innovative configuration could hence be useful to mitigate these adverse effects occurring at high temperature in standard ID-tag substrates like lithium niobate [8]. It could also extend the use of the identification principle for harsh environments, where substrates with limited performances in terms of K^2 and α such as langasite ($La_3Ga_5SiO_{14}$ often called LGS), langatate ($La_3Ga_{5.5}Ta_{0.5}O_{14}$ known as LGT) or AlN/Sapphire are commonly used [9]. The development of high temperature devices is of major importance for industrial domains such as automotive or aerospace since it can lead to lower costs and higher production efficiency [10,11].

Here, we present a proof of concept of a configuration with connected IDTs for SAW-based ID-tag applications. The position and the number of connected IDTs will generate an identification code, similar to the standard operation. Such principle of coding (using the spacing and the number of conventional IDTs with the same dimensions), as well as the method of device interrogation (using conventional RF pulse), distinguish the structure suggested here from previous structures studied in [12,13].

In the following sections, the numerical comparison between the conventional configuration and the proposed one are presented. Experimental results obtained on 128°Y-X cut lithium niobate (abbreviated LN-Y128 here) are then discussed in order to demonstrate the interest of the configuration with connected IDTs. To go even further, results achieved with a low K^2 langasite substrate are presented. Finally, measurements up to 600°C on both substrates with two different types of metallization for the IDTs are reported.

II. Materials and Methods

Two different configurations (with the same wavelength λ=24 µm) are compared in order to study the influence of the design on the amplitude of the peaks creating the code. The first one, conventional, has one IDT and two reflectors (see Fig. 1). The central IDT contains 11 pairs of fingers. The reflectors contain 21 fingers each. They are located at a distance of 60 λ and 90 λ from the central IDT, respectively. Both have the same aperture, equal to 1000 µm. In the second configuration, shown in Fig. 2, three IDTs (identical to those previously described) are connected together. Neither configuration has been optimized; to have similar delays in both configurations, the distances between the connected IDTs are 120 λ and 180 λ, respectively. The metallization ratio is fixed to 50% for both devices.

The COM parameters were extracted first, from harmonic admittance simulations by finite elements method (FEM). They were then used to compute the electrical response of the two configurations, using standard P-Matrix algorithms.

The devices were fabricated using an optical lithography process and a positive resist, on a lithium niobate Y128°-X cut and an LGS (0°,138.5°,26.3°) substrate. A 150 nm thin layer of aluminum (Al), gold (Au/Cr) or platinum (Pt) was deposited by RF sputtering. The process was finalized by wet etching for the aluminum layer or by ion beam etching for the gold and the platinum layers. The devices were characterized at room temperature using a probe station (Suss MicroTec PM5) and a network analyzer (VNA Agilent-N5230A). Measurements were done in the frequency domain (center frequency was fixed to the SAW device resonance and a span of 100MHz was used) and then converted to the time domain directly by the network analyzer. High temperature measurements were performed up to 600°C (the higher limit of our setup) in air, using a RF probe station (S-1160, Signatone) equipped with a high temperature probing system (S-1060, Signatone). GS Z-probes were modified in-house by adding a water-cooling element, in order to withstand high temperatures during the characterization. The evolution of the crystalline structure was analyzed by X-ray diffraction (XRD) before and after high temperature measurements.

III. Results and Discussion

A. Proof of concept

The inverse fast Fourier transform (IFFT) envelopes of the simulated S_{11} frequency responses for devices #1 and #2 are presented in Fig. 3. By targeting the first two peaks, it appears that the red curve, which corresponds to the two directly transmitted signals in device #2, has a higher amplitude than the blue curve which corresponds to the two reflections in device #1. More precisely, for the design #1 (red curve), the first two peaks are due to several sequential electromechanical conversions, namely: one at the IDT for the signal emission, two at the reflectors and a last one at the IDT for the reception. In design #2 (blue curve), the first two peaks are only due to two electromechanical conversions (the first one at the IDT for

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the transmission and the second one at the other IDT for the reception). So the difference around 16 dB is mostly due to the number of electromechanical conversions. The higher the number, the lower the received energy because only a part of the energy can be converted (related to the K^2 value).

For device #2, some slight modification in the signal shape can be observed. This requires an additional study which is planned for future work.

The first experimental results on LN-Y128 with Al electrodes are also promising. Fig. 4 corresponds to the time domain signals and shows the same behavior as in the simulation. This good agreement between experimental and numerical results validates the model for future simulations. This also confirms the interesting features of the configuration with connected IDTs.

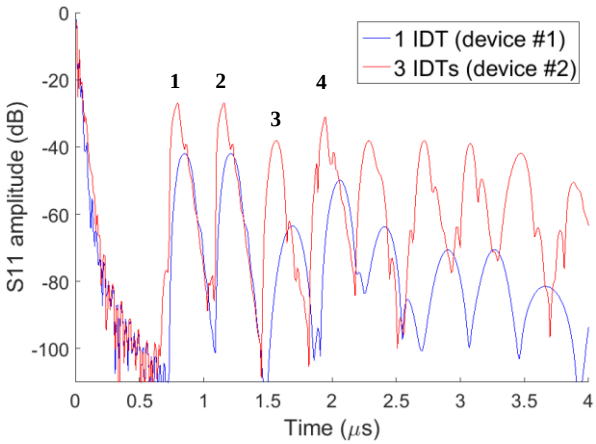

Fig. 3. Simulated reflection coefficient in the time domain of devices #1 and #2 on a LN-Y128 substrate with Al electrodes.

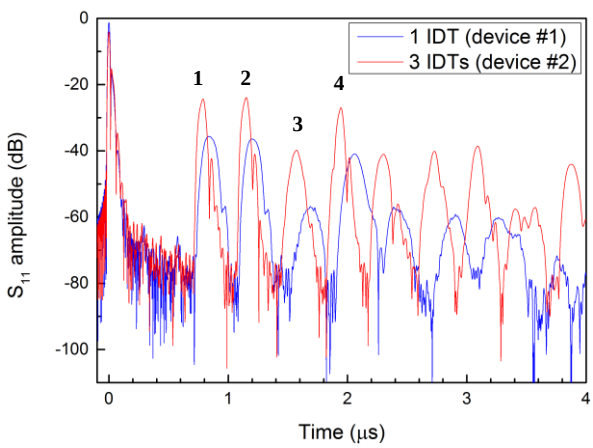

Fig. 4. Experimental reflection coefficient in the time domain of devices #1 and #2 on a LN-Y128 substrate with Al electrodes.

B. *Extension to substrates with low coupling or higher losses*

This proof of concept made on lithium niobate can be extended to langasite in order to enable the use of ID-tags at high temperature. Fig. 5 and 6 depicts the comparison between simulations and experiments for device #1 and device #2 based on an LGS substrate with an Al metallization. Simulations show that the peaks coming from a reflection have a lower amplitude than the experimental noise level, which is around -80 dB. Therefore, it is consistent with the fact that no signal is measured in the standard configuration with reflectors. This is mostly due to the low coupling value (K^2=0.34%, [14]) and the reflection in the LGS device. By contrast, with the three connected IDTs configuration, a signal can be identified from the noise. Each peak corresponds to a direct transmission between the IDTs.

Even if the detected amplitude is 40 dB lower than the one measured on lithium niobate, this confirms the interest of the configuration with connected IDTs on a substrate with a low K^2 value. The amplitude difference is partly due to the differences in K^2 values between the two substrates.

It is also interesting to see that the third peak from device #2, which corresponds to the reflection between two connected IDTs, is not detected. This confirms that the reflection is much smaller than the direct transmission.

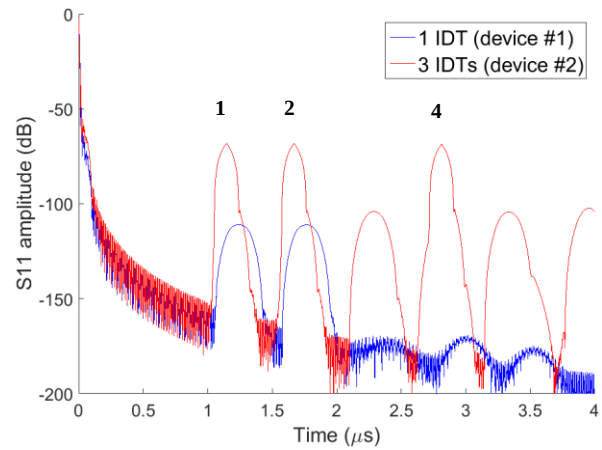

Fig. 5. Simulated reflection coefficient in the time domain of devices #1 and #2 on an LGS substrate with Al electrodes.

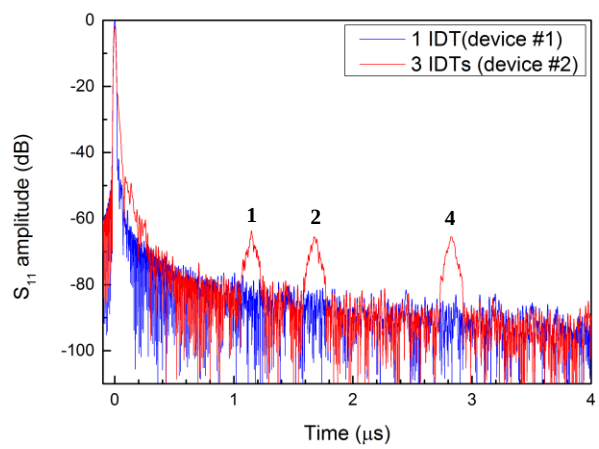

Fig. 6. Experimental reflection coefficient in the time domain of devices #1 and #2 on an LGS substrate with Al electrodes.

C. *High temperature measurements*

According to the Literature, lithium niobate is not well suited for high temperature applications [15]. On the contrary, due to its thermal stability (up to 1000°C), LGS is currently the standard [16]. Fig. 7 and 8 show the results obtained up to 600°C with Au/Cr electrodes on LN-Y128 and LGS, respectively. After 45 minutes at 600°C, no more signal is

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detectable on the LN-Y128, in contrast with the LGS substrate. The increased attenuation on LGS comes from the physical destruction of several IDT electrodes by the scratch with probe-head tips that have slipped-off due to the thermal expansion of the substrate. The images of the devices after the measurements at 600°C show that the gold electrodes are also significantly damaged by heat (see Fig. 9). Based on [17], the thin film agglomeration is related to the Tammann temperature, which is defined as:

$$T_{Tammann}\,(°K) = \frac{T_{melting}\,(°K)}{2} \quad (1)$$

For gold, the value of the Tammann temperature is 395°C. It has been largely exceeded in the previous measurements, which may explain the observed phenomenon of agglomeration. Therefore, the signal loss on the LN-Y128 substrate, and its decrease on the LGS substrate after 45 minutes at 600°C, are also potentially related to the damage of gold electrodes.

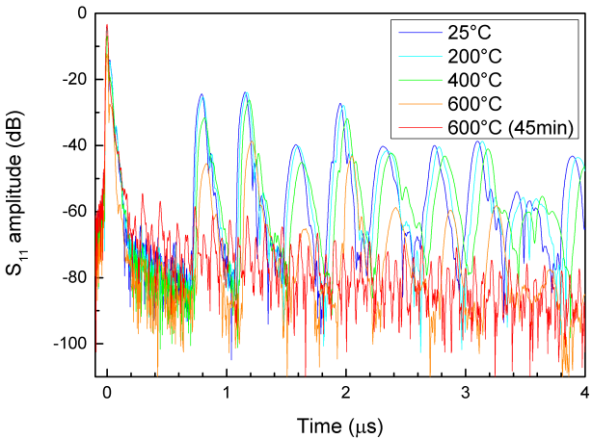

Fig. 7. Experimental reflection coefficient in the time domain up to 600°C of device #2 on a LN-Y128 substrate with Au/Cr electrodes.

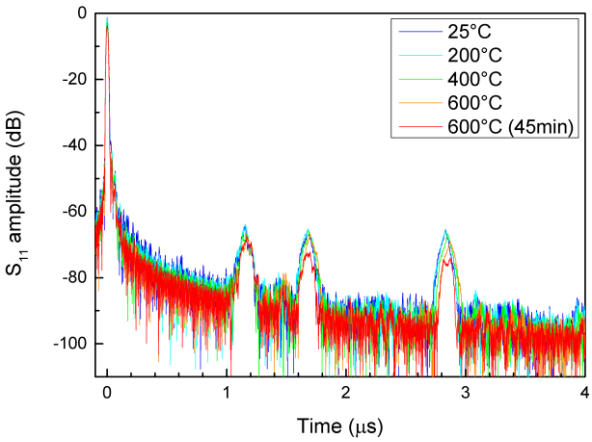

Fig. 8. Experimental reflection coefficient in the time domain up to 600°C of device #2 on an LGS substrate with Au/Cr electrodes.

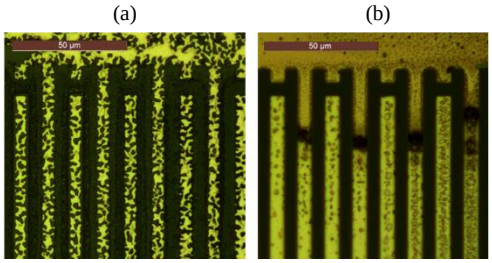

Fig. 9. Optical images of the Au/Cr electrodes (a) on a LN-Y128 substrate and (b) on an LGS substrate after measurements up to 600°C.

In order to remove this ambiguity, devices made with platinum electrodes were considered. Indeed, the Tammann temperature of platinum is 748°C which is high enough for the investigated temperature range. The results obtained at high temperature with the LN-Y128 and LGS substrates are given in Fig. 10 and 11, respectively. After 45 minutes at 600°C, the signals are still detectable, even for the lithium niobate substrate, which was quite unexpected. The latter shows a moderate signal attenuation with temperature, but remains operational at 600°C. The optical images of Pt electrodes on LN-Y128 and LGS at 600°C confirm that the platinum electrodes are less damaged than the gold ones (see Fig. 12).

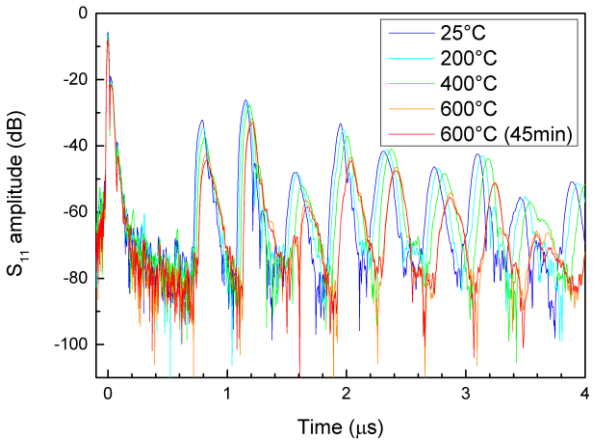

Fig. 10. Experimental reflection coefficient in the time domain up to 600°C of device #2 on a LN-Y128 substrate with Pt electrodes.

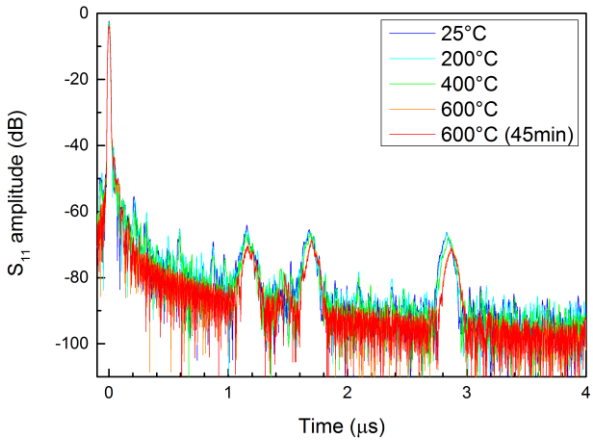

Fig. 11. Experimental reflection coefficient in the time domain up to 600°C of device #2 on an LGS substrate with Pt electrodes.

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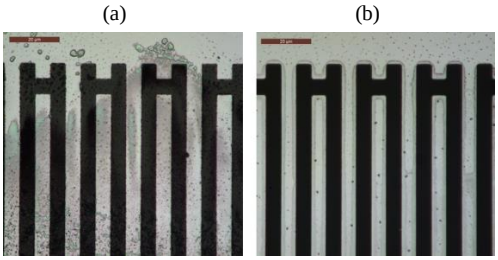

Fig. 12. Optical images of the Pt electrodes (a) on a LN-Y128 substrate and (b) on an LGS substrate after measurement up to 600°C.

In Fig. 13 and 14, a perfect superposition of the curves at room temperature before and after measurements at 600°C is observed. This clearly demonstrates that platinum has not been damaged and that both substrates (LN-Y128 and LGS) exhibit a completely reversible behavior for measurements up to 600°C. These results highlight the potential of the LN-Y128 to be used at least up to 600°C for a duration of the order of one hour. Further investigations will be conducted considering higher temperatures and longer operating times.

Moreover, the time delay (56 ns for the second peak on LN-Y128 with Pt electrodes) observed in the measurements between 25°C and 600°C looks promising for the use of the configuration with connected IDTs as a temperature sensor.

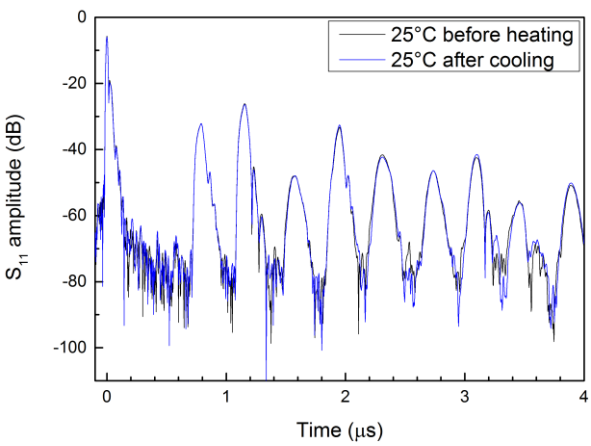

Fig. 13. Experimental reflection coefficient in the time domain at 25°C from device #2 on a LN-Y128 substrate with Pt electrodes before and after high temperature measurements.

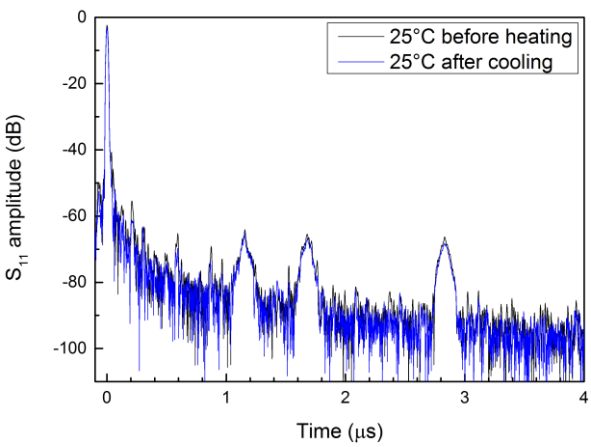

Fig. 14. Experimental reflection coefficient in the time domain at 25°C from device #2 on an LGS substrate with Pt electrodes before and after high temperature measurements.

Fig. 15 summarizes the amplitude decrease and the time delay increase with the temperature on the devices with Au/Cr and Pt electrodes. Data was taken from the second peak, as plotted in Fig. 7 and 10. In the configuration with three connected IDTs, the first two peaks corresponding to the direct transmissions should have the same amplitude (considering that propagation losses are negligible for the LN-Y128 substrate). This is for example the case shown in Fig. 7 with Au/Cr electrodes. However, in Fig. 10 with Pt electrodes, the two peaks do not have perfectly identical amplitudes. This can be explained by a very small platinum residue that has not been etched in the 120 λ gap. Peak 1, which correspond to the propagation in the 120 λ gap, is affected by this residue. However peak 2, which is linked to a propagation in the 180 λ gap, is unaffected and was therefore used for amplitude comparisons. In Fig. 15, it is interesting to notice that the sharp amplitude decrease in the case of gold electrodes with respect to platinum is consistent with the fact that the gold electrodes were damaged.

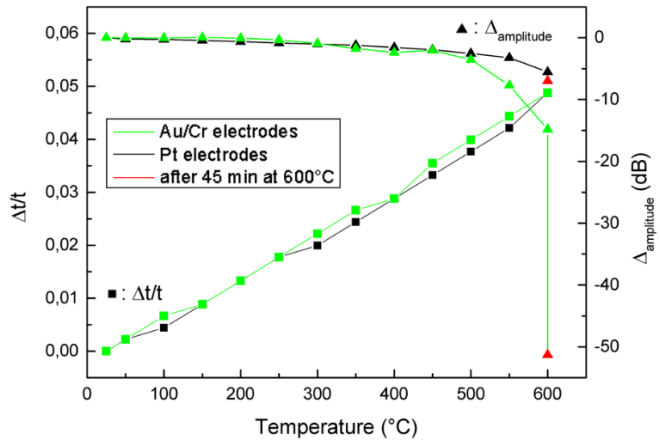

Fig. 15. Experimental evolution of the amplitude and the time delay with temperature for device #2 made on a LN-Y128 with Au/Cr and Pt electrodes.

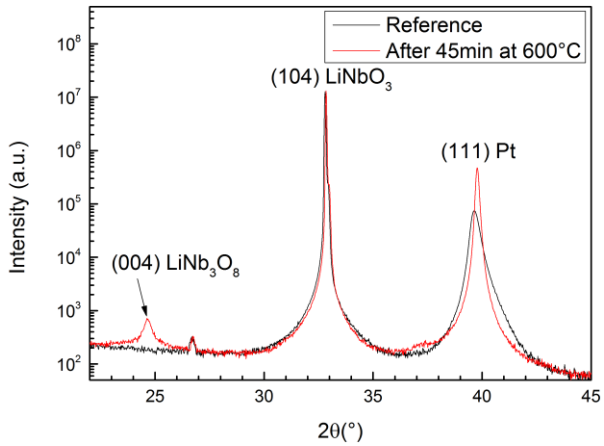

Fig. 16. θ-2θ XRD patterns of the LN-Y128 device #2 with Pt electrodes before and after high temperature measurements.

Finally, the XRD analysis of the LN-Y128 substrate before and after measurements at 600°C is given in Fig. 16. A new peak appears at 2θ=24.6°, which corresponds to the (004) orientation of lithium triniobate ($LiNb_3O_8$). However, the

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appearance of $LiNb_3O_8$ does not seem to be detrimental for measurements up to 600°C for 45 minutes.

D. Discussion

The configuration with three connected IDTs presents a clear interest for ID-tags, but some drawbacks need to be taken into consideration. Compared with the conventional structure with reflectors (device #1), the size of the configuration with connected IDTs is larger (device #2). Moreover, there is a splitting of the RF power (of the interrogation signal) between the IDTs. This means that there is a maximum number of IDTs that can be connected together. After a given number, the signal amplitude will be lower than the one reflected in the conventional configuration, limiting the interest of the structure with connected IDTs. It could be interesting to deepen the comparison of both structures by considering an optimized design for the reflectors, as it has already been studied in [18].

Numerical simulations were done with an increased number of IDTs. In a configuration with 4 connected IDTs it is possible to generate a code thanks to the 6 peaks resulting from direct transmissions, whereas 6 reflectors are needed to obtain 6 peaks resulting from single reflections. The details of the studied devices are given in Fig. 17. For clarity, only the one-way direct transmissions have been represented.

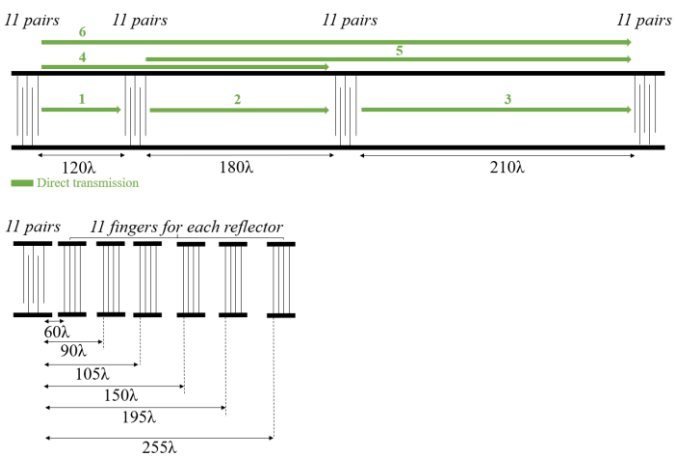

Fig. 17. Configuration with 4 connected IDTs (device #3) and its equivalent with reflectors (device #4).

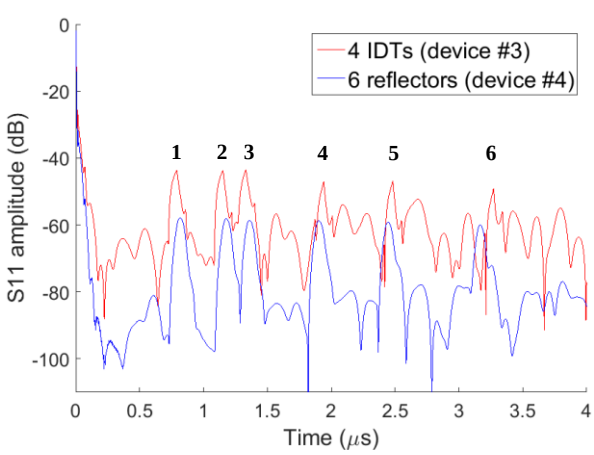

Fig. 18. Simulated reflection coefficient in the time domain of devices #3 and #4.

The simulations (see Fig. 18) show that the larger the number of connected IDTs is, the more difficult it is to identify the direct transmission peaks. This can be explained by the fact that all electrically connected IDTs re-emit the signal when it comes to some of them. This phenomenon does not appear in the equivalent structure, even with a high number of reflectors. Moreover, the electrical interaction between connected IDTs also leads to complicated impedance matching, in contrast to the configuration with only one IDT and several reflectors. The subsequent antenna matching is an important feature to consider for remote interrogation.

In short, there is a tradeoff to be found between the amplitude level increase on one side, and the signal quality and ease of matching on the other side. With a low number of connected IDTs, the advantages of this device overcome their drawbacks in comparison to conventional designs. Thus, the concept suggested here is intended for applications that require the use of sensors with an identification functionality in harsh environments, but with a limited number of codes.

IV. Conclusion

A reflective delay line configuration with connected IDTs for ID-tag applications was presented and tested. The amplitude of the peaks is increased due to direct transmission, in comparison to the conventional configuration (i.e. with reflectors).

Experimental results obtained on LN-Y128 and LGS are in good agreement with simulations. This configuration with connected IDTs can further improve the performance of devices based on the well-known LN-Y128 substrate and help mitigate potential losses in harsh environments. It has also been shown that this design can be really useful for substrates where the detection of ID-tag peaks is almost impossible, like in LGS that has a poor coupling.

Electrical characterizations up to 600°C with platinum electrodes confirm the interest of the structure for operation under harsh conditions such as in high temperature environments, notably for temperature sensing. The concept can be used on LGS, which is well suited for high temperature applications, but also on LN-Y128 up to 600°C at least for 45 minutes, which was not initially expected.

Design tradeoffs regarding the signal amplitude, purity and impedance were also discussed. With the right design, this structure is very promising for wireless interrogation at long distances and at high temperature.

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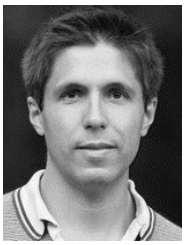

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