Paper III

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Z-Path SAW RFID Tag

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***Abstract*—Surface acoustic wave (SAW) radio-frequency identification (RFID) tags are soon expected to be produced in very high volumes. The size and cost of a SAW RFID tag will be key parameters for many applications. Therefore, it is of primary importance to reduce the chip size. In this work, we describe the design principles of a 2.4-GHz SAW RFID tag that is significantly smaller than earlier reported tags. We also present simulated and experimental results.**

The coded signal should arrive at the reader with a certain delay (typically about 1 μs), i.e., after the reception of environmental echoes. If the tag uses a bidirectional interdigital transducer (IDT), space for the initial delay is needed on both sides of the IDT. In this work, we replace the bidirectional IDT by a unidirectional one. This halves the space required by the initial delay because all the code reflectors must now be placed on the same side of the IDT. We reduce tag size even further by using a Z-path geometry in which the same space in x-direction is used for both the initial delay and the code reflectors. Chip length is thus determined only by the space required by the code reflectors.

I. Introduction

Surface acoustic wave (SAW) radio-frequency identification (RFID) tags are soon expected to be in high-volume production as there is a large market for passive RF identification. The size and cost of an RFID tag are naturally key parameters for many applications. Therefore, one of the most important goals in SAW tag design is the reduction of chip size.

However, the number of distinct codes to be realized and the used frequency band impose limitations on the delays of coded responses and, consequently, on tag size. For a SAW RFID tag based on time position encoding, each code reflector occupies a slot corresponding to certain duration of time as illustrated schematically in Fig. 1. These slots form groups of, for example, five slots. When such grouping is used, one of the first four slots of each group is occupied by a reflector; the fifth one, the guard slot, is always left empty. One group thus corresponds to two bits of data. The width of a single slot is $\Delta t = 1/B$ where B is the used frequency band. Thus, for a SAW tag operating at 2.45 GHz and using a 40-MHz band, the slots are 25 ns wide. Typically, about 20 code reflectors are needed for a reasonably great number of codes. This corresponds to a time delay of about $20 \cdot 5 \cdot 25$ ns = 2.5 μs. In addition, an initial delay for environmental echoes of about 1 μs, corresponding to 2 mm of chip space on lithium niobate, is also necessary.

In previously reported designs [1], [2], code reflectors are situated on both sides of a bidirectional interdigital transducer (IDT) as sketched in Fig. 2. In this geometry, the 1-μs initial delay is needed on both sides of the IDT. For a tag having 14 code reflectors, as the tag studied in this work, this results in a total chip length of greater than 10 mm. The eventual increase of data capacity (up to 128 or even 256 bits) will inevitably result in even larger chip sizes or demand more complicated encoding methods [3].

A multichannel geometry [1], [4] (see Fig. 3), which combines long and short delays in one acoustic channel, has a slightly reduced total chip length. However, it uses more space in the transverse direction and the space for the initial delay is still present on both sides of the IDT. Moreover, the parallel connection of tracks inevitably increases losses.

In this work, we replace the bidirectional IDT with a unidirectional one, similar to that presented in [5]. This halves the space needed for the initial delay as all the reflectors must now be placed on the same side of the IDT as illustrated in Fig. 4. A further reduction of device size can be achieved by folding the acoustic channel into a Z-path by using two strongly reflecting inclined reflectors.

II. Z-Path Design

We study a SAW RFID tag that is comprised of a unidirectional IDT, two strongly reflecting inclined reflectors (each having 21 open-circuited floating electrodes) folding the acoustic channel into a Z-path, and 14 code reflectors. In this configuration, the same space in the x-direction (the initial direction of propagation) is used for both the initial delay and the code reflectors. The device geometry is illustrated schematically in Fig. 5.

A. Transducer

As an IDT, we use a single-phase, unidirectional transducer (SPUDT) [5]. This type of transducer generates wave propagation predominantly in one direction, which reduces losses compared to the bidirectional case of Fig. 2. The SPUDT used in this work consists of a reflector section of open-circuited floating electrodes sandwiched by two identical standard IDT sections whose electrodes have alternating polarities.

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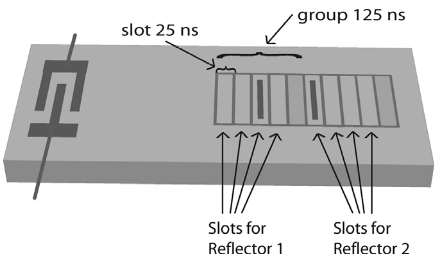

Fig. 1. SAW tag based on time position encoding.

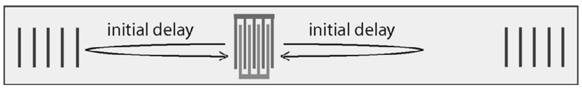

Fig. 2. SAW tag using a bidirectional IDT.

The SPUDT was characterized through delay line simulations and experiments. As our simulator accepts only inline device geometries, no simulated results are available for Z-path delay lines. However, a theoretical estimate for SPUDT losses was obtained by simulating an inline delay line consisting of two identical SPUDTs facing each other and separated by 300 μm. The absolute value of the simulated S_{21} parameter for this device is shown in Fig. 6. The minimum insertion loss (MIL) is -4.7 dB.

Losses were further studied by using experimental delay line data. Experiments on inline delay lines of different lengths revealed the SPUDT losses to be about -6.4 dB (per two SPUDTs) and the propagation loss about -5.3 dB (per 3.8 mm). A Z-path delay line having an acoustic path length of about 3.8 mm had a MIL of -19.0 dB as shown by the $|S_{21}|$ plot in Fig. 7. Losses due to the inclined reflectors can be estimated by subtracting the SPUDT losses and the propagation losses from the MIL of the Z-path delay line. This gives about -7 dB, which is a realistic estimate considering the reflection strength of the inclined reflectors.

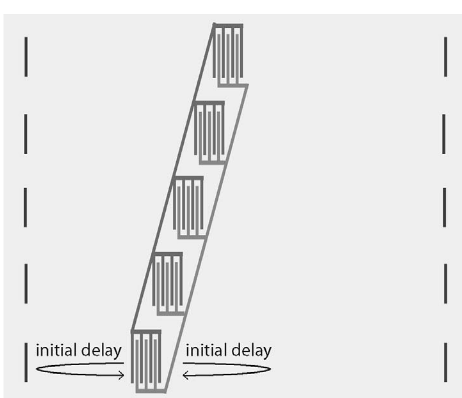

Fig. 3. SAW tag having a multichannel geometry.

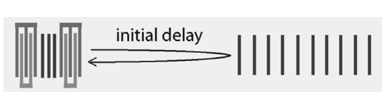

Fig. 4. SAW tag using a unidirectional IDT.

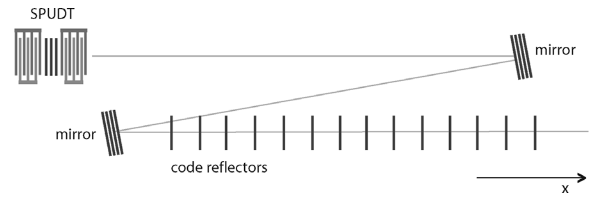

Fig. 5. Z-path geometry.

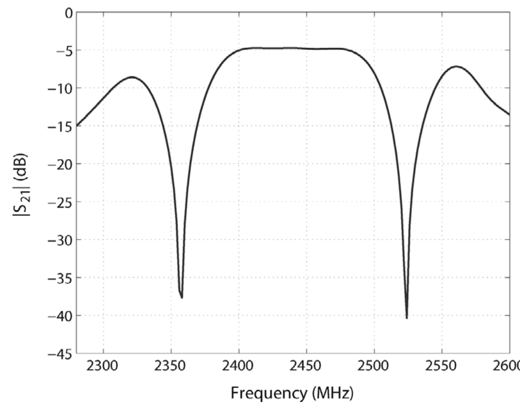

Fig. 6. $|S_{21}|$ for an inline delay line consisting of two identical SPUDTs facing each other and separated by 300 μm. Simulation.

B. Z-Path Geometry

Fig. 8 illustrates the reflection at the first inclined reflector: α_i is the angle of incidence, α_r is the angle of reflection, and $\theta_r = \alpha_i + \alpha_r$ is the direction of the reflected wave vector. Due to the anisotropy of the substrate material (128°-$LiNbO_3$), the phase velocity of the surface acoustic wave depends on the propagation direction. Therefore, the angles α_i and α_r are not equal but have to be, as does the rest of the tag geometry, determined using slowness data.

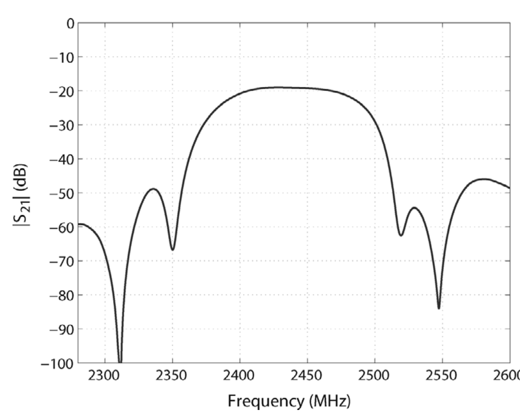

Fig. 7. $|S_{21}|$ for a Z-path delay line consisting of two identical SPUDTs separated by a Z-path and having an acoustic path length of about 3.8 mm. Experimental data.

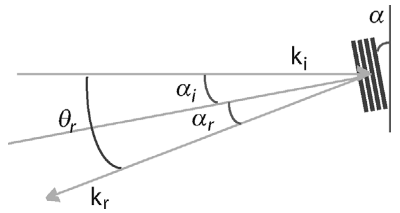

Fig. 8. Reflection of the wave vector at the first mirror.

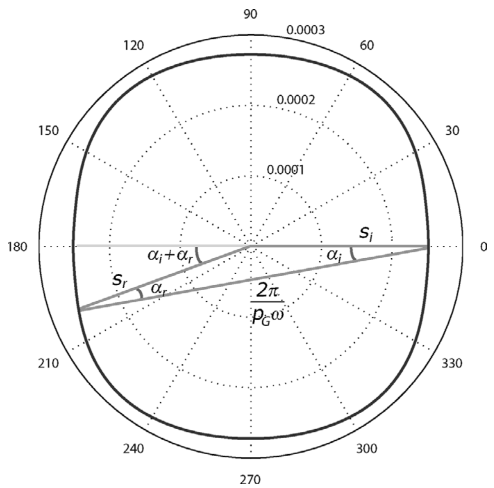

Fig. 9. Phase slowness s versus wave vector direction θ for 128°-LiNbO$_3$. (s is in seconds/meter and θ in degrees.)

1. Phase Velocity: The dependence of phase velocity V on the wave vector angle θ can be obtained easily from the slowness curve, which presents phase slowness $s = 1/V$ as a function of θ. The slowness curve for 128°-LiNbO$_3$ (calculated using a Green's function based software [6]) is shown in Fig. 9. The Cartesian plot of Fig. 10 presents phase velocity as a function of wave vector angle for the range $-45° \leq \theta \leq 45°$.

2. Power Flow Angle: Due to the anisotropy of the substrate material, phase and energy velocities are not equal. The power flow angle (i.e., the difference between the wave vector direction θ and the power flow direction θ_e) is defined as [7]:

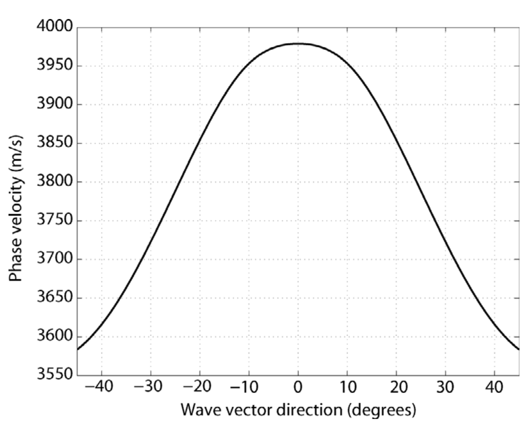

Fig. 10. SAW velocity V versus wave vector direction θ for 128°-LiNbO$_3$.

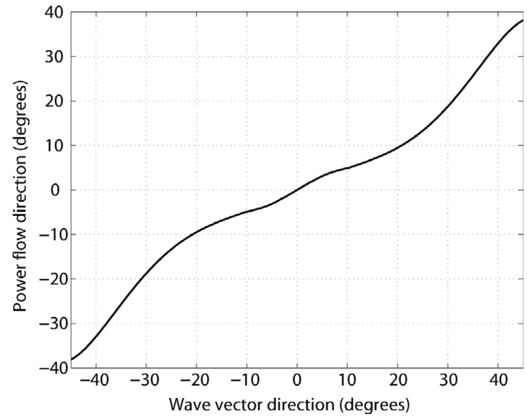

Fig. 11. Power flow direction θ_e versus wave vector direction θ for 128°-LiNbO$_3$.

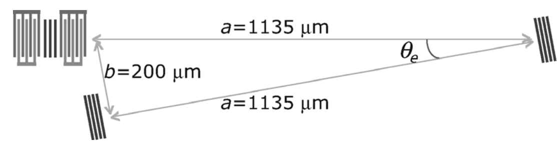

Fig. 12. Power flow direction and distances determining the mirror positions.

$$\theta - \theta_e = \arctan\left(\frac{1}{V}\frac{dV}{d\theta}\right). \tag{1}$$

Eq. (1) can be used to obtain the dependence of the power flow direction θ_e on the wave vector direction θ. Fig. 11 shows this dependence for $-45° \leq \theta \leq 45$ in the case of 128°-LiNbO$_3$. It can be seen that, for this range of wave vector angles, $\theta_e < \theta$. It also is to be noted that θ_e can be considered directly proportional to θ only for the approximate range of $-5° < \theta < 5°$.

3. Geometry Calculations: When calculating the tag geometry, we must first make sure that the SAW beam (the power) reflected by the first inclined mirror will not miss the second one: the angle θ_e of the once reflected acoustic ray is determined by the desired positions of the inclined reflectors (see Fig. 12). For an initial delay of 1200 ns, a distance of approximately $a = 1135$ μm is required between the IDT and the first inclined reflector. Using this same distance between the two inclined mirrors and choosing $b = 200$ μm as the separation of the IDT and the second mirror, the angle θ_e becomes approximately 200/1135 rad $\approx 10.10°$. The corresponding direction of the reflected wave vector can be read from Fig. 11, which gives $\theta_r \approx 20.96°$.

The mirror pitch p_G and the angles α_i and α_r can be determined using the slowness curve. Applying the cosine theorem in the triangle drawn in Fig. 9 gives:

$$\left(\frac{2\pi}{p_G\omega}\right)^2 = s_i^2 + s_r^2 + 2s_is_r\cos(\alpha_i + \alpha_r), \tag{2}$$

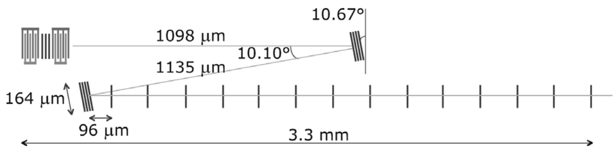

Fig. 13. Z-path design.

where ω is the center frequency of the device, and s_i and s_r are the phase slownesses of the waves incident and reflected at the first inclined mirror, respectively. Using the data obtained from the slowness calculations, i.e.:

$$s_i = s(\theta = 0°) = 2.513 \cdot 10^{-4} \text{ s/m}, \quad (3)$$

$$s_r = s(\theta = 20.96°) = 2.603 \cdot 10^{-4} \text{ s/m}, \quad (4)$$

and setting $\omega = 2\pi \cdot 2441.75$ MHz yields $p_G \approx 0.814$ μm. The sine theorem then gives $\alpha_i \approx 10.67°$ and $\alpha_r \approx 10.29°$. The inclination angle α of the mirrors is equal to α_i.

C. Code Reflectors

The final step of the design is placing the code reflectors at correct positions. The position of the first reflector is determined by the initial delay. Each of the following reflectors occupies one of the first four 25-ns slots of a group of five slots. To keep the first design simple, we place each code reflector in the first slot of the group, and hence expect delays of 125 ns between code reflections.

If we use identical reflectors, the coded signal will consist of pulses with gradually decreasing amplitudes as energy is lost due to reflections and free-surface propagation. In order to obtain response pulses with uniform amplitudes [8], the reflectivities of the reflectors must gradually increase along the acoustic path. The reflectivities are adjusted by varying the number of electrodes in the reflectors and the metal ratio m/p (m is the width of an electrode, p is the pitch of the electrodes) of the reflectors.

For long structures, like SAW RFID tags, diffraction effects cannot be ignored. However, for our design, the device geometry (transducer aperture w compared to wavelength λ) is such that we stay relatively well in the near-field region. The Fresnel limit x_c is obtained from [9]:

$$x_c = (1 - \gamma)\frac{w^2}{\lambda}, \quad (5)$$

where the anisotropy parameter γ has a value of -0.43 for 128°-$LiNbO_3$ [10]. For our device, $w = 155$ μm and $\lambda = 1.6$ μm, which gives $x_c = 21.5$ mm. The round-trip path lengths for the code reflections range from 4.7 mm to 10.9 mm.

D. Tag Response

The response of the tag designed above and having the geometry shown in Fig. 13 is presented in Fig. 14. The uniformity of peaks is excellent, but the inclined reflectors are still to be optimized for a lower level of losses.

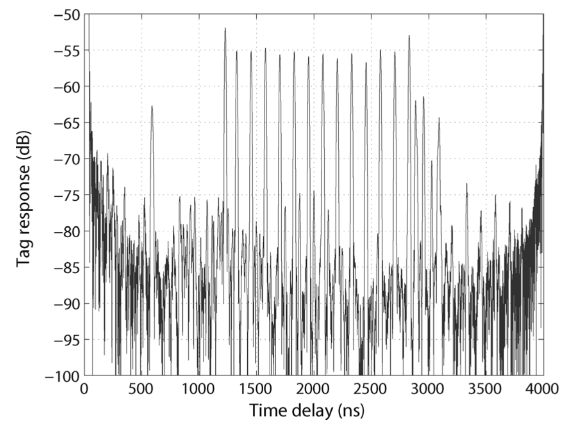

Fig. 14. Response of Z-path tag. Experimental data.

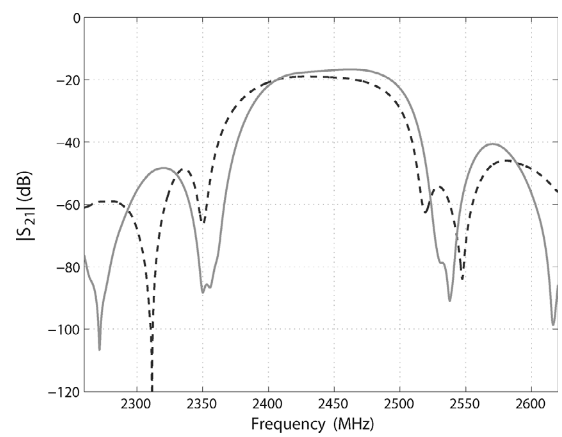

Fig. 15. $|S_{21}|$ for a Z-path delay line. Original (dashed) and improved (solid) designs. Experimental data.

It is obvious from Fig. 7 that the SPUDTs and the inclined reflectors are not yet optimal. First, they do not have the desired center frequency: the innermost notches in Fig. 7 give 2435.6 MHz for the center frequency of the SPUDTs, and the outermost notches yield 2430.3 MHz for that of the inclined reflectors. In order to shift both components to 2441.75 MHz, we scale the size of these structures accordingly. Second, the passband of the inclined reflectors is wider than necessary. We attempt to make it as narrow as that of the SPUDTs by increasing the number of fingers in the inclined reflectors from 21 to 28. This also should decrease losses. We also attempt to reduce the total losses by optimizing the geometry of the inclined reflectors: based on experimental data, their optimal inclination angle is 10.51°. The absolute value of the S_{21} parameter of a Z-path delay line before and after these modifications is shown in Fig. 15. The IDT and the reflector bands now have the same center frequency of 2445.1 MHz (a bit higher than expected), the reflector band is nearly as narrow as the IDT band, and the minimum insertion loss is now -16.6 dB.

III. Conclusions

In this work, we have shown—through simulations and experiments—that the size of a SAW RFID tag can be significantly reduced by replacing a bidirectional IDT with a SPUDT, and by folding the acoustic channel into a Z-path by using two strongly reflecting inclined reflectors. Due to the anisotropy of the substrate material (128°-$LiNbO_3$), phase and energy velocities of a SAW are not equal. Therefore, we have used slowness data when calculating the device geometry.

The advantage of the Z-path geometry is that the same space in x-direction can be used for both the initial delay and the code reflectors. This means that the chip size is determined only by the space required by the code reflectors. The proposed configuration is especially advantageous for tags having a relatively long initial delay compared to the space required by the code reflectors. For such devices, a chip size of less than 2 mm by 1 mm (at 2.45 GHz) is realizable.

Another advantage of the Z-path geometry is that the direction of the twice reflected wave always remains parallel to the initial direction of propagation. This makes the device operation practically insensitive to temperature variations of size and velocities.

Acknowledgments

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Sanna Härmä was born in Kotka, Finland, in 1977. She received the Master of Science and Licentiate of Science (in Technology) degrees from the Helsinki University of Technology (TKK), Espoo, Finland, in 2001 and 2007, and the Bachelor of Arts degree (in French philology) from the University of Helsinki, Helsinki, Finland, in 2007.

She has worked as a research assistant at the Laboratory of Biomedical Engineering, TKK, as a research scientist at the Materials Physics Laboratory, TKK, as a design engineer at Thales Microsonics, Sophia-Antipolis, France, and as a subject teacher in Helsinki, Finland. She is currently preparing a D.Sc. thesis on SAW RFID tags at the Laboratory of Optics and Molecular Materials, TKK.

Victor P. Plessky was born in Belarus in 1952. He received the Ph.D. degree from the Moscow Physical-Technical Institute in 1978 and the D.Sc. degree from the Institute of Radio Engineering and Electronics (IRE, Russian Academy of Sciences, Moscow) in 1987. He was awarded the USSR National Award for Young Scientists in 1984.

He started to work at IRE in 1978 as a junior researcher and was promoted to Laboratory Director in 1987. In 1991, he also worked as a part-time professor at the Patris Lumumba University, Moscow. He received the full professor title in 1995 from the Russian Government.

In 1992, he joined Ascom Microsystems SA, Bevaix, Switzerland, where he worked as a SAW project manager. Since 1997, he has lectured on various SAW topics at the Helsinki University of Technology (TKK), Espoo, Finland, as a visiting professor and currently holds a docentship at TKK. In 1998, he started to work at the Neuchâtel, Switzerland office of Thomson Microsonics (later Thales Microsonics, finally Temex). Since 2002 he has worked as a consultant.

Dr. Plessky has been engaged in research on semiconductor physics, SAW physics (new types of waves, scattering and reflection on surface irregularities, and laser generation of SAW), SAW device development (filters, delay lines, and reflective array compressors), and magnetostatic wave studies. His current interests focus on SAW physics and low-loss SAW filter development.

Clinton S. Hartmann received his B.S. degree in electrical engineering from the University of Texas at Austin in 1967. In 1968 and 1969, he received his S.M. and E.E. degrees from the Massachusetts Institute of Technology at Cambridge. In 1976, he was named The Outstanding Young Electrical Engineer in the United States by Eta Kappa Nu, the electrical engineering honor society. He is a member of Tau Beta Phi, Eta Kappa Nu, and Sigma Xi.

Mr. Hartmann began his career in 1969 at Texas Instruments, Dallas, TX, where he later achieved the rank of TI Fellow for his pioneering work in the field of surface acoustic wave devices and applications. During this period, he invented numerous SAW devices including the SAW resonator, which has become the most widely used SAW device in the world. In 1979, Hartmann cofounded RF Monolithics, Inc., Dallas, TX, a SAW device company that subsequently became a successful public company. In 1985, he founded Hartmann Research, Inc., Dallas, TX, where he invented and developed SAW device types including the electrode width controlled single-phase unidirectional transducer (EWC/SPUDT), a filter commonly used in television sets and cell phones. Hartmann is currently President of RF SAW Inc., Dallas, TX, which he founded in 1998. RF SAW is a leader in the design and development of SAW-based radio-frequency identification (RFID) technology and product solutions for supply chain, asset management, security, and government organization applications worldwide. During his 30-year career, Hartmann has invented many SAW devices that are in common use today. He holds more than 80 U.S. patents plus numerous international patents. He has approximately 80 publications. His current research interests focus on Global RFID SAW devices and physics.

William Steichen received his engineering diploma from the Institut National Polytechnique de Grenoble (INPG), Grenoble, France, in 1978. He has been working for the Thales Group for 22 years in the field of acoustics (underwater, medical echography, SAW and BAW devices). In the last 5 years, he has been at Temex, Sophia-Antipolis, France, as R&D manager, SAW devices. He was a codirector of the Laboratoire de Physique et de Microsonique, a joint laboratory between Temex and Femto-ST, Besançon, France. Since July 2007, he has been with Thales-Safare in Sophia-Antipolis, France.