Review on SAW RFID Tags

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***Abstract*— SAW-tags were invented more than 30 years ago, but only nowadays the conditions are united for mass-application of this technology: the devices in 2.4GHz ISM band can be routinely produced with optical lithography and Internet is available for global access to the tag databases. Perspectives of the "Internet of Things, I-o-T" will demand trillions of cheap tags and sensors. The SAW-tags overcome semiconductor based analogues in many aspects: they are true passive devices, can be "read" at a few meter distance with readers radiating 2 to 3 orders lower power levels, they are cheap and can operate in robust environment. Passive SAW tags are easily combined with sensors. Even the "anti-collision" problem (simultaneous reading of many tags situated nearby) has solutions sufficient for many practical applications. In this paper we discuss state-of-the–art in development of SAW-tags. The design approaches will be reviewed – and the most optimal tag designs are demonstrated, as well as encoding methods. We discuss the ways to reduce size and cost of these devices. A few practical examples of tags with simple time-position coding will be demonstrated with 10^6 different codes. Phase coded devices allow further radical increase of the number of codes, the price to pay being reduction of the reading distance. We also discuss exciting perspectives of using Ultra Wide Band (UWB) technology emerging now for communication applications in SAW-tag systems. Wide frequency band available in this standard is a great opportunity for SAW-tags to radically reduce their size to about 1x1 mm^2 keeping practically infinite number of possible different codes. Finally, the reader technology will be discussed as well as detailed comparison made between SAW-tags and IC-based semiconductor device.**

I. Introduction

In this paper we briefly review the current status of development of RFID tags based on the Surface Acoustic Wave (SAW) technology. We discuss mainly the tag devices, omitting issues related to the readers design, and the corresponding signal processing issues.

The first radio identification (RFID) systems appeared already during World War II for military applications, namely, for identification of planes. However, it is only now that the technical conditions are united for a wide use of radio frequency identification (RFID). The two key issues for the RFID technology are the number of different codes that can be 'written' on a tag and the possibility to store, transfer, and communicate information. Due to the ongoing progress of semiconductor technology, mass production of such devices at a low cost has become possible. More specifically, micro- and nanometer lithographic technology allows for the fabrication of very small tags (with a chip size on the order of 1 μ and smaller) operating at the GHz-range where sufficiently wide frequency bands are available. These industrial, scientific, and medical (ISM) frequency bands can be used without licensing with a limited radiated power. The wide frequency bands finally allow for a practically infinite number of different codes to be written and read at microsecond time intervals. As to the second key issue, the omnipresent internet, intranet, and similar communication networks enable the processing of databases and developing of smart systems that use the information automatically read from RFID tags. We can point out that the dramatic development of mobile phones (that only combine a transmitter and a receiver, both used in radio communications for a century by now) was based exactly on the same two reasons: first, the development of technology allowing the use of high frequencies, wide frequency bands and, finally a large number of subscribers and, second, computer databases with high-speed data links enabling fast communication. The type of RFID tag introduced in this chapter, the surface acoustic wave (SAW) tag, is in many aspects similar to RF SAW filters that are widely used in mobile phones. SAW tags and SAW filters use basically the same technology.

RFID tags will be omnipresent. Here is the list of possible application (by far not complete):

- Traffic control of vehicles, wagons, ships, etc.
- Identification of containers, pallets, bags in airports, etc.
- Individual goods control and inventory in stocks, shops, etc.
- Tracing of animals and products of animal origin
- Tracing of wild animals, marking of trees in forests, etc.
- access to buildings, parking, restricted areas, computers

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- ambient assisted living for disabled and older people
- identification of parts, equipment, machines, cars, assembled on conveyer lines
- tracing of dangerous and explosive substances
- security and guard services

The applications mentioned above will demand trillions of tags per year, which may result in the industry larger then whole SAW industry of today. For the first time possible mass application of tags was predicted by C. Hartmann many years ago [1].

II. ACTIVE AND PASSIVE RFID TAGS

Semiconductor RFID tags can be subdivided into two categories depending on whether they are passive or active. While active tags usually have an on-board battery, passive tags power their circuitry by using a part of the interrogation signal energy transmitted by an external reader. The incorporation of a battery makes a device expensive, limits it's life-time, and furthermore, makes it questionable in environmental aspects. The application of a rectifier stage for extracting power from the interrogation signal, together with the limited licensed radiation power of the read-out signal, restricts the reading distance to a very limited range. SAW tags can be considered as true passive devices because they do not require any power supply. They simply reflect the interrogation signal in a coded form that carries the identification information. SAW tags employ SAW delay lines and feature low losses, large delay times, and small dimensions. In addition, they have a simple and robust structure.

As compared to the widely used barcode, both semiconductor-based and SAW-based RFID tags have the following obvious advantages:

- They can be read automatically, that is, without human presence. This allows for an unambiguous identification of objects, people, and animals.
- They do not need to be in line-of-sight to the reader nor is any particular tag orientation demanded.
- They can have a reading distance as large as 10 m and even larger, depending on the system used. For barcodes, reading distance is limited to about 30 cm.

III. SAW RFID TAGS

The main feature of SAW tags is that their operation is based on micro-acoustics of *piezoelectric crystals* instead of semiconductor physics. The principal advantage of these devices is their total passiveness: they do not require any DC power because they merely reflect the interrogation signal, being a linear device. Moreover, the interrogation signal can be about 100 times smaller (about 2 mV on the tag antenna) than for integrated circuit (IC) based tags. Another attractive feature of SAW tags is their simple structure. SAW tags are fabricated using single-metal-layer photolithographic technology. Admittedly, operation in the microwave region requires submicron lithography (about 0.3μ-wide electrodes), which is a standard tool today in IC fabrication. This enables the fabrication of devices working at the 2.45-GHz frequency band reserved globally for ISM applications. SAW tags utilize the unique nature of piezoelectric materials which allows for a transformation of electromagnetic waves into 100 000 times slower surface acoustic waves. SAW tags can hence function as delay lines and provide a sufficient delay (with a relatively small substrate length) for temporally separating the tag response signal from the read-out signal.

A. SAW tags vs. IC tags

Compared to the IC-based semiconductor tags SAW tags demonstrate the following advantages [2]:

- SAW tags operate with low level RF pulses of about 10 mW. IC tags at the same distance require a continuous radiation of a few watts.
- SAW tags operate in the 2.45-GHz ISM band - compliant with RF emission regulations throughout the world. The use of IC tags demands specific certification.
- SAW tags can be put on metal objects. SAW tag systems achieve greater penetration into pallets containing metal or liquid items (RFSAW, 2004).
- SAW tag readers have a substantially higher interference resistance than IC tag readers radiating a few watts in the same frequency as Bluetooth, WLAN, etc.
- The reading process of SAW tags permits a direct and accurate measurement of the tag temperature SAW tags thus have an inherent capability of functioning as sensors.
- SAW tags are very robust and can be used in challenging environments (e.g. withstand high levels of as well as elevated temperatures). Semiconductor-based tags are more sensitive to such harsh conditions.

Since IC tags include memory and a processor, any information in these tags can be re-written and the volume of information written in a tag is relatively large. This is considered as principal advantage of the IC tags, which are small in size and relatively cheap. IC tags can also reach a reading distance of a few meters.

But the possibility to re-write tags will inevitably make readers easily accessible and tag information easily read without authorization or even falsified.

Since manufacturing SAW tags only requires one photolithographic step, they will in mass production inevitably become cheaper than IC-based tags which also need expensive antenna for harvesting EM power. To achieve a reading distance comparable to that of SAW tag readers, IC tag readers have to radiate 100 to 1000 times higher RF power, up to a few watts. Such a concentration of electromagnetic radiation may lead to health hazards and would create strong interference with other communications systems using the same frequency range. SAW-tag also can easily incorporate sensor functions.

B. *Principle of operation*

The operation of SAW devices is based on piezoelectricity. This is, in general terms, a coupling between a material's electrical and mechanical properties: in certain dielectric crystals, the application of mechanical stress produces an electric polarization and, conversely, such a crystal undergoes a mechanical distortion when an electric field is applied. This property is used in SAW devices and in many other applications to produce a mechanical output from an electrical input or vice versa. In SAW devices the transduction between an electrical signal and an acoustic wave is achieved by utilizing an interdigital transducer (IDT), consisting of two interlaced comb-like metal structures deposited on the surface of a piezoelectric substrate. The principle of operation of a reflector-based SAW tag is shown schematically in Fig. 1. A reader emits an interrogation pulse, which is received by the tag antenna, directly connected to an IDT.

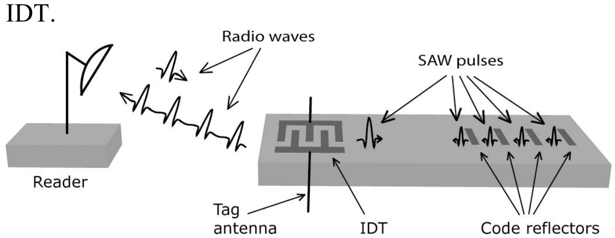

Figure 1. Operation of a SAW tag system.

The IDT transforms the electrical signal into a nano-scale surface acoustic wave, which is a mechanical wave of particle displacements. The generated SAW pulse then propagates along the surface of the substrate, which is usually made of a strong piezoelectric material such as lithium niobate ($LiNbO_3$). The SAW pulse is partially reflected and partially transmitted by each of the so-called code reflectors, placed at precisely determined positions on the chip. These reflectors usually consist of one or a few narrow aluminum strips. The reflected SAW returning to the IDT thus carries a code based on the positions of the reflectors. In other words, this encoding method is based on the time delays of reflected pulses. It is known as time position encoding or pulse position modulation (PPM) and is described in further detail in section 3.3. When the train of reflected SAWs finally returns to the IDT, the acoustic signal is reconverted into an electrical form and retransmitted by the tag antenna. The response signal is then detected and decoded by the reader. In SAW tags, a surface acoustic wave is hence used for 'reading' a sub-micron 'barcode' of properly arranged reflectors. In real reader systems the described pulse signals are rarely used and more simple frequency domain reading methods are used in which S11(f) of the tags is measured [29]. They allow for cheaper reader designs.

IV. Milestones of SAW-tags history

A. *SAW tags based on IDTs*

First SAW tags were proposed in 70s [3], [4] and included the multi-IDT structures in one or a few acoustic channels. Fig.2 schematically demonstrated the idea of such devices. The 1-track IDT tags (Fig.2a) suffer too series defects to be suitable for application demanding large number of codes. Big size, high losses, multiple reflections, difficulty of coding, can be mentioned among the problems.

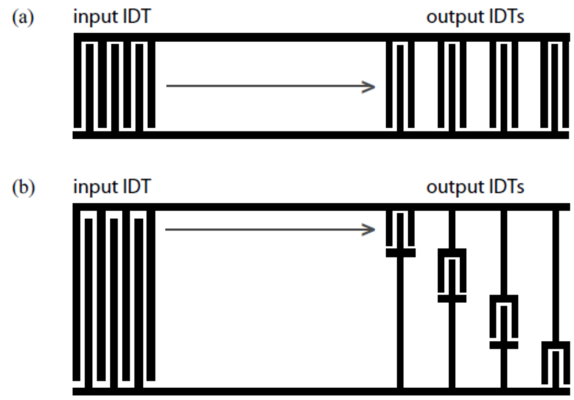

Figure 2 Transducer based SAW tags

In multi-track case the multiple reflections are partly reduced, but the losses are higher and the width of device increased.

B. *Reflector based tags*

In X-Cyte tags [4] the multi-track design included separate transducers in each acoustic channel and reflectors on both sides (Fig.3).

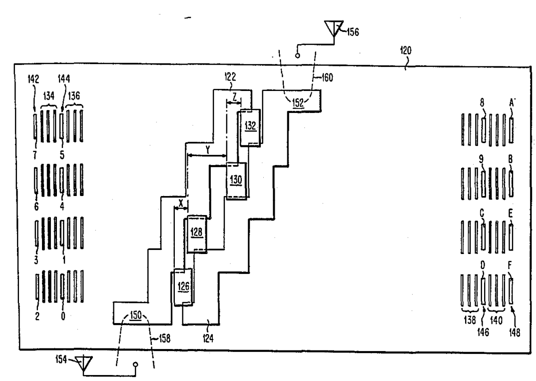
Figure 3. X-Cyte tag

Reflector based tag with folded propagation path of SAWs allows to reduce 2 times the size. Original layout (Fig.3) of X-Cyte tag resulted in further decrease of size in propagation direction, while multi-track geometry finally increases the chip area. The main defect of multi-track design is increased losses, which cannot be compensated. Proposed in [4] coding based on the change of phase is demanding for technology. We tried this topology in year 1994 [5] for 2.4 GHz tags (Fig.4 below). Although the device had very reasonable performance the realization of phase coding was impossible at that time and 2.4 GHz frequency. The device had no reference reflector.

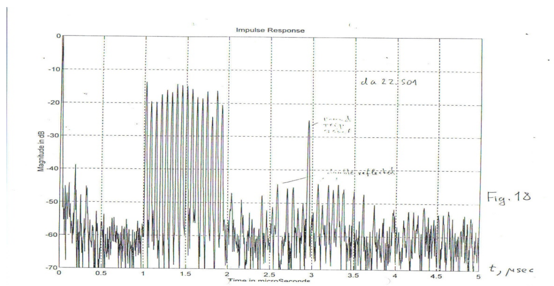

Figure 4. Measured response of SAW-tag device; arbitrary loss reference level

C. Siemens SAW tags

One of the first commercial operations of SAW-tags RFID systems were realized by Siemens [6], [28]. Their tags used 2.45 GHz center frequency with an amplitude modulation of 33 bit positions. 4 acoustic tracks placed on both sides of the transducer were used. The SAW ID tags were used in Munich subway. The ID tags were mounted on the side of the railway wagons and the reader units were placed along the rails and linked to a central computer. The system showed good interference immunity even under harsh conditions.

D. BaumerIdent tags

These tags were developed first in small Swiss company TAGIX by R. Stierlin later transferred to BaumerIdent company [7].

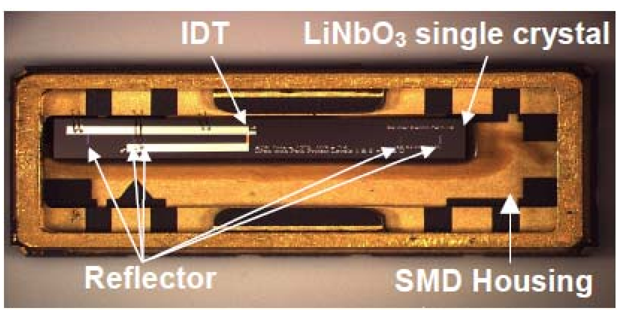

Figure 5. SAW tag from BaumerIdent

The device operated in 2.4 GHz ISM band with the split finger IDT using 3rd harmonic. In one track are situated 5 open-circuit λ/2 wide reflectors on both sides of the IDT. "Time position coding" was used providing 10000 different codes. The design included a few innovations:

- Calibration reflector was introduced to simplify compensation for temperature and technology shifts during reading and deciphering of the code
- Time position coding was implemented [8], [9] allowing more reliable reading of the code.
- Reflectors were off-set by fraction of wavelength in 2 sub-channels to reduce parasitic multiple reflection

E. C. Hartmann's « Global tag »

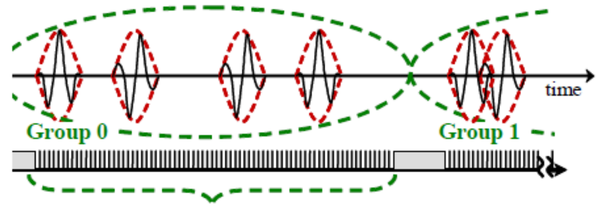

Figure 6. Combined time position and phase coding

Significant step to practically infinite number of codes was made by C. Hartmann [10-15]. In his coding scheme the time position is used but time slots for the position of the centre of a pulse are radically reduced due to prescribing to each slot some phase which is systematically growing along the array of slots inside given group of slots, Fig.6. Although the pulse width remains much wider than one time slot the pulse position can be localized due to phase information. Code capacitance up to 256 bits is predicted and devices with 128 bits were demonstrated [12]. The open-circuit reflectors were used with their shape adopted for compensation of diffraction.

F. Other SAW-tag design ideas

D. Malocha and coworkers recently developed "Orthogonal Frequency Coding" for SAW-tags [16]. They use carefully designed rather narrow band reflectors arranged in a way that when one reflector has maximal reflectivity the reflectivity of the others is close to zero. Such system allows reducing losses, because the reflectors can be rather strong. This approach can be applied to sensors and for identification of limited number of sensors, but it hardly can be used for ID tags with large number of codes. Potentially a bank of SAW resonators with slightly different frequencies can be used as ID tag. One of variants of such tag, although based on FBARs, is described by A. Ronnekleive and co-authors [17]. High Q-factor of SAW resonators would allow to use lower frequency ISM bands (434MHz and 868 MHz), where the available frequency band is too narrow for reflector delay line tags described above. This approach demands a bank of independent high Q-factor resonators and its realization seems to be difficult.

V. DESIGN OF SAW TAGS

A. Frequency bands and data capacity

Although the idea of SAW tags was already proposed decades ago (Davies et al., 1975, [18]), its final commercial breakthrough has not yet realized. In order for the SAW tag to become a commercially attractive product for mass applications, its data capacity must be at least 20 to 32 bits, that is, a few million codes or, better, billions.
The number of different codes is determined by the ***BT*** product (***B*** is the used frequency band and ***T*** is the coding time), as suggested by Shannon's formula (Shannon, 1948, [19]). As a SAW tag must be small and cheap, we cannot use more than 2 µs to 4 µs for coding delay. These delays

correspond to propagation distances of 8 mm and 16 mm. If a data capacity of 32 bits (better 64 bits or 128 bits) is desired, a frequency band of 16 MHz (or 32 MHz, or 64 MHz) is needed. Such frequency bands are available only at relatively high frequencies. Effectively, the only suitable frequency range available globally is the ISM band from 2400 MHz to 2483.5 MHz. This band is now extensively used around the world for local communication systems: Bluetooth, WLAN, wireless keyboards, etc.

Achieving a sufficient number of codes in a SAW tag hence requires the use of the 2.45-GHz range. This calls for submicron photolithographic tools as the narrowest linewidths needed at this frequency range are on the order of 0.3 µm to 0.4 µm. It is to be noted that this requirement is rather modest in comparison with the state-of-the-art IC technology operating with a resolution down to 0.05 µm. SAW tag technology can hence reuse equipment from older generations of IC, which decreases the fabrication cost.

An identification code can be written on the SAW tag in time positions, amplitude, phase, or other suitable signal characteristics of the reflected pulses. The reflected pulses represent the symbols of the tag response signal and can code for one or more bits each. The first commercial SAW tags, designed according to these principles, are currently used in demanding industrial environments, more specifically, for automation of car assembly lines. The number of unique codes commercially achievable at present is rather limited: on the order of 10 000. New ideas are currently being developed aiming at a radical increase in the data capacity of SAW tags to 64 or even 128 bits (Hartmann, [10-15]).

B. *Best SAW tag geometry*

Without giving the proofs we can formulate most advanced for today principles of SAW tag design:

- One track must be used with unidirectional transdcer (SPUDT) to avoid bi-directionality loss
- Open finger reflectors with variable duty factor give low loss; diffraction compensation can be used
- Time position coding; 4 slots per group is close to optimal for achieving maximal number of codes using given total delay. In “Global tag” proposed by C. Hartmann the number of position is much higher and the group of slots may include a few pulses.
- Initial delay about 1 microsecond remains necessary
- Two or three calibration reflectors (with fixed position) must be used.
- Error correction and other auxiliary function may “eat” rather big number of reflectors which cannot be used for coding but occupy space.

C. *Time position encoding*

SAW RFID tags can be encoded in several ways. Currently existing SAW tag products use the so called time position encoding (Plessky et al., 1995 [5]; Stierlin & Küng, [8], [9]), which represents the most straightforward way of data encoding in SAW tags. This is the main method currently used in commercial SAW tags (Reindl & Shrena, 2004 [7]; Stelzer et al., 2004 [20]).

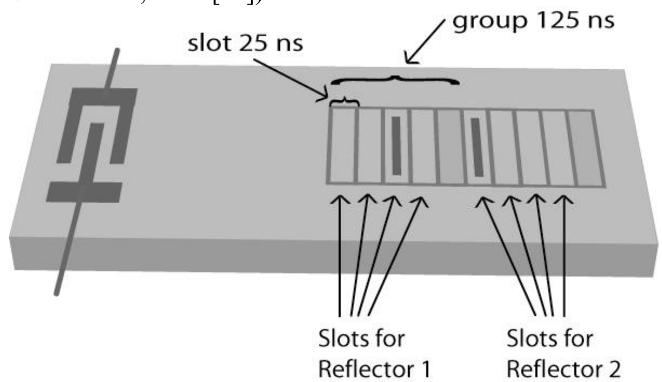

Figure 7. Principle of time position encoding in SAW tags.

In this encoding scheme, the total time delay is divided into slots of certain duration. The slot width is roughly equal to the time width Δt of the pulses, that is, Δt = 1/B, where B is the frequency band of the overall system (actually determined by the band of signals radiated by the reader). At 2.45 GHz, a band of 40 MHz is typically used, and the corresponding slot width is thus 25 ns. The slots form groups of, for example, five slots. For a tag using such grouping, one of the first four slots of each group is occupied by a reflector while the fifth one, the guard slot, is always left empty (see Fig. 7). Each reflector thus has four possible positions (equal to 2 bits of data) and the total number of different realizable codes is 4n for a tag having n reflectors. Ten code reflectors will thus yield about 10^6 distinct codes. When all the reflectors are placed in-line in one acoustic path, the chip space required by these ten reflectors is about 2.5 mm. The advantage of this encoding method is that one always has the same number of reflectors, which makes it easier to design a SAW tag with uniform amplitudes of response signals. Also, for the reader, the problem then simplifies to the search of a single response in a given group of time slots.

To maximize the number of codes (for a given total coding time) in the time position encoding scheme, about 3 to 4 slots per group must be used. However, in practical devices (BaumerIdent, CTR), as in that shown in Fig. 8, decimal groups are also employed. In such a scheme, a reflector can occupy one of ten possible positions. Commercially available SAW tags have a data capacity of 10 000 different codes, which in the decimal time position system corresponds to four code reflectors.

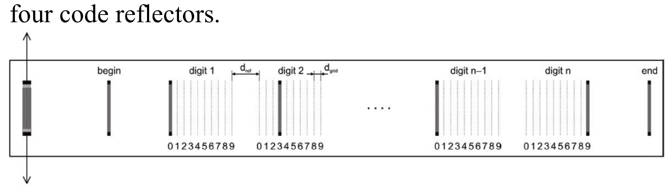

Figure 8. Practical example of time position encoding. (Stelzer et al., 2004)

To provide uniform amplitudes of responses (or any other desired variation of amplitudes with the pulse number), the strength of reflectors must be carefully adjusted beginning from the very last and most strong reflector. Sometimes it is impossible to keep the uniform magnitudes of reflectors up to very first responses – it would demand too week reflectors at the beginning of reflector array and higher amplitudes of first responses may be an option [12].

D. Phase encoding

For time position encoding, the exact coordinate of a particular reflector is not so important. It must be within a 25-ns time slot, which corresponds to about 60 wave periods ad 2.4 GHz. The calibration reflectors help to account for inaccuracies in position due to temperature, technology variations, and other shifts. A code reflector often consists of only one or a few electrodes. A single reflector electrode has a width of about 0.4 µm to 0.6 µm, that is, it is significantly narrower than the slot it occupies. The slot width of 25 ns corresponds to about 50 µm of physical space.

If the phases of the reflected pulses could be measured accurately, the coding capacity would increase significantly. Phase encoding has been discussed for many years but not yet implemented in commercial products. The idea of phase coding is simple: by displacing the reflectors slightly, phase shifts can be realized and phase coding implemented. Fig. 9 illustrates the principle of introducing phase shifts of 90° by shifting reflector positions by multiples of $\lambda/8$ (Härmä et al., 2008, [21]). In such a case, each reflector can have 4 phase positions, which adds 2 additional bits to time position encoding. The above described SAW tag with ten code reflectors will then have 240 variants of codes, 40 bits, or about 10^{12} different codes. This is a large number: for every human being on Earth, there will be about 150 tags available with different codes never repeated. Phase coding can be combined with time position encoding in a more clever way (C. Hartmann [10-15]): instead of keeping time slots unchanged and introducing phase modulation of the reflectors, it is proposed to narrow the time slots and radically increase the number of slots in a group, keeping the duration of time for the whole group unchanged. Each slot is assigned a definite phase of the reflector if the reflector is placed there. In this modulation scheme, the phase is used to determine the time position of the reflected pulse. It is evident that the uncertainty of measurement of phase of reflected responses depends on the signal-to-noise ratio (Kuypers et al., 2008, [22]). The needed strength of signal increases with increasing accuracy of phase values used for encoding. Optimal methods for phase encoding and decoding are under intensive investigation ([23]).

E. Encoding technology

Whatever encoding scheme employed, each SAW tag produced has a unique physical appearance. Currently, for the manufacture of only 10 000 different codes, the images of all these tags are placed on a large - but still reasonable - number of photomasks. This technology will evidently be too expensive for 10^6 codes and totally unrealizable for 10^{13} different codes.

An idea of a double-stage photolithography process, where in the first stage all reflectors in all possible positions are produced (or at least exposed) with high accuracy, and subsequently all redundant reflectors are deleted, say, with some fast and programmable tool, was already proposed. However, it has not yet been implemented on mass production scale. Programmable reflectors were proposed [27] at the expense of loosing tag's passiveness.

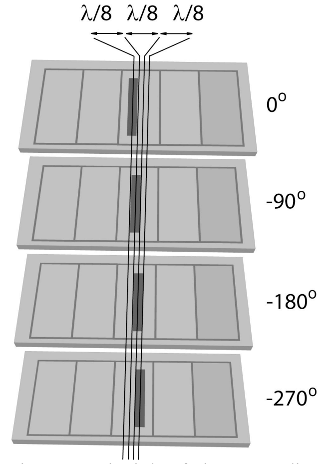

Figure 9. Principle of phase encoding

VI. Developments in SAW tags

The main goals of SAW tag design include a reduction of device losses, a reduction of device size, and an enhancement of data capacity. A combination of time position encoding and phase encoding provides a means for increasing the information capacity, as described in above section. This section presents ideas of further solutions and shows that a small device size can be achieved for SAW tags simultaneously with a sufficiently large data capacity.

A. Examples of recent design of SAW tags

Figure 10 shows a typical time response of a SAW tag. In this case, FEM/BEM software (FEMSAW description on www.gvrtrade.com) has been used to simulate the performance of a tag having 14 code reflectors.

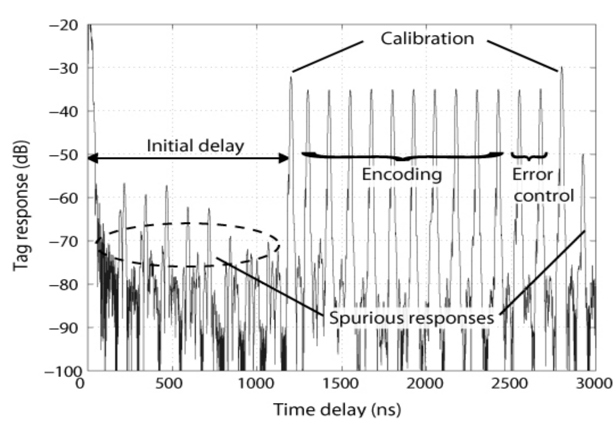

Figure 10. Simulated SAW tag response

As illustrated by the mask image in Fig. 11, ten of the reflectors are used for encoding itself; the first and the last

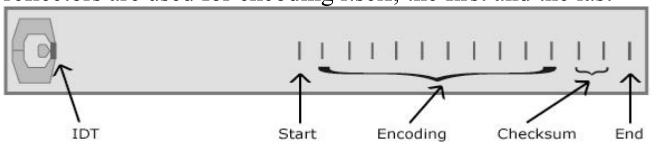

Figure 11. Mask image of a reflector-based SAW RFID tag

reflector are used for calibration and are typically designed to have stronger responses than the others; while the two reflectors preceding the very last one are used for error control, for creating a checksum. The reflector array is designed to produce uniform amplitudes for code reflections, in order to achieve a maximal read range.

Amplitudes of response signals are adjusted by gradually increasing the reflectivity of code reflectors, by adding electrodes to reflectors and by increasing their width. This is done in order to compensate for the losses due to propagation on the substrate surface and to reflections from preceding code reflectors. As mentioned above, a SAW tag must provide certain time delay in order to separate the response signal from the read-out signal. The reflected signals must be received by the reader only after a delay sufficient for the environmental echoes (reflections from walls or other nearby objects) to die away. An adequate initial delay is typically about 1 µs and is facilitated by leaving about 2 mm of empty space on the substrate between the IDT and the code reflectors. The free-surface SAW velocity on LiNbO3 is about 4000 m/s.

B. Loss reduction in SAW tags

A standard IDT, as depicted in Fig. 1 and Fig. 2 consists of electrodes with alternating polarities. As it transforms the electrical signal into an acoustic form, it generates surface acoustic wave propagation equally in both directions. When such a bidirectional IDT is used in SAW tags, half of the signal energy is already lost in transduction.

This problem can be overcome by using a unidirectional IDT that only generates wave propagation in one direction. For a similar reason, SAW-tags with several parallel acoustic channels will have a higher loss level than a device wherein all reflectors are situated in the same channel.

However, typical unidirectional transducers (more specifically, single-phase unidirectional transducers, SPUDTs) include electrodes with a width of λ/8, where λ is the wavelength of SAW on the piezoelectric substrate. At 2.45 GHz, λ/8 is about 0.2 µm. This makes SPUDT-type transducers inaccessible for the photolithography currently used in SAW industry.

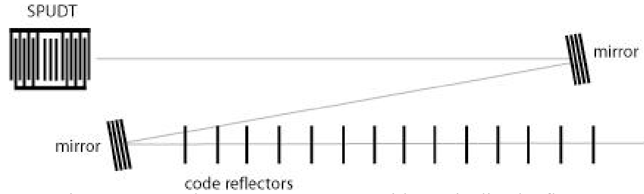

Figure 12. Z-path SAW tag geometry with two inclined reflectors.

Recently, however, a SPUDT especially designed for SAW tag applications was proposed (Hartmann & Plessky, 2007 , [14]) exploiting the fact that, on 128°-LiNbO3, the reflectivity of short-circuited electrodes can be close to zero at some metal thickness and electrode width. The proposed transducer uses□/4-wide (and wider) electrodes and can be manufactured using the optical photolithography.

Currently used tags, that use a bidirectional IDT, have a loss level on the order of -55 dB for 10 000 codes. This will be reduced to about -40 dB for SAW tags with a unidirectional IDT and 10^6 codes (Härmä et al., 2008, [24]). The unidirectional transducer may include 0.3-µm-wide electrodes. Also the reflectors must be rather narrow: for some cases, reflector electrodes must have a width of 0.3 µm to 0.4 µm. Therefore, a reliable photolithography capable of producing the linewidth of 0.3 microns is needed. In addition to reduced losses, the use of a SPUDT in SAW tags has the advantage of a lower level of parasitic reflections, including reflections from the transducer itself.

C. Size reduction of SAW tags

Replacing the bidirectional IDT with a unidirectional IDT also serves to reduce the chip size. SAW tags using a bidirectional transducer are normally designed to have their reflectors on both sides of the transducer. In this case, space for the initial delay must also exist on both sides, which results in an inefficient use of the substrate area. When a unidirectional transducer is employed, all reflectors must be placed on the same side of the transducer and only one initial delay is needed.

A further reduction of chip size can be achieved by folding the channel used for SAW propagation. A Z-path SAW tag has been designed, fabricated and tested [24] that uses two inclined, strongly reflecting mirrors (each consisting of an array of open-circuit metal strips), as shown in Fig. 12. Although such folding demands two additional reflectors (and four reflections of the signal), which inevitably results in additional losses on the order of -5 dB to -10 dB, the reading distance is reduced less than 2 times. This can be an acceptable price to pay for a significant reduction of size and cost of a SAW tag. The size of the chip in 0X direction was reduced to about 3 mm.

D. Ultra-wideband SAW tags

The currently emerging ultra-wideband (UWB) technology offers many attractive possibilities for the development of SAW RFID tags. According to the regulation of the United States Federal Communications Commission (FCC) (Breed, 2005, [25]), an UWB device is a device emitting signals with a fractional bandwidth greater than 20% or a bandwidth of at least 500 MHz. A SAW tag operating at 2.5 GHz with a band of 500 MHz would satisfy this criterion. The UWB band being much wider than the 2.45-GHz ISM band, a certain value of BT product, determining the data capacity of a tag, can now be achieved with a significantly shorter coding delay, which enables a considerable reduction of tag size. For example, with B = 500 MHz, a BT of 200 only requires a coding time of 400 ns instead of the 2 μs typical for 2.45-GHz SAW tags. The total chip size can then be smaller than 0.5 x 1.0 mm^2. A shorter coding time also implies lower losses. A propagation time of 400 ns only corresponds to about -3 dB propagation loss. Another interesting possibility is to have signal processing partly performed within a SAW tag using, for example, a chirp transducer (Ianelli & Koslar, 2004, [26]), as illustrated in Fig. 13. This will allow for a matched-to-signal processing of the tag response, which, after being modified within the tag, will be different from the environmental echoes of the interrogation signal, also received by the reader. This makes the system more resistant to environmental interference, as the reader is now able to distinguish between the signal reflected by the SAW tag and that reflected by objects outside the tag. As the principle of the ultra-wideband technology is to reuse an already occupied frequency spectrum but with very low power, an UWB SAW tag system will also have an additional advantage of very low transmitted power levels.

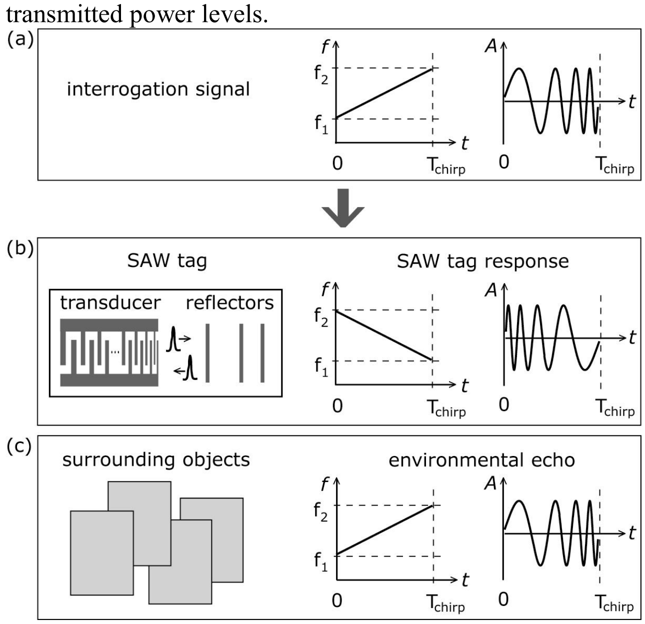

Figure 13. Interrogation process for an ultra-wideband SAW tag. (a) An up-chirp linear frequency-modulated signal is used for interrogation. (b) The signal is compressed by the chirp transducer, reflected by code reflectors, and expanded by the transducer. The output signal has a dispersion opposite to the interrogation signal. (c) Reflections from surrounding objects have the same dispersion as the interrogation signal.

VII. DISCUSSION

The market demands small size, low cost, and environmentally sound RFID tags. That excludes devices consuming power from batteries. Both semiconductor-based tags and SAW tags can be read remotely, and both are small in size. They do not require maintenance and their life-time is limited only by the usual product time of the circuitry. However, SAW RFID tags and passive semiconductor RFID tags are based on fundamentally different physical principles. In this section, we compare in detail these two approaches.

A. Power issues in SAW tags and in IC tags

The main feature of SAW RFID tags is that they do not use any autonomous power supply such as batteries. Moreover, they do not include any such circuitry that would need to be powered. SAW tags are truly passive devices that merely reflect the interrogation signal. This results in a linear operation at any signal level, even at a very low one. The signal energy of the SAW tag response must of course be sufficiently high for the reader to be able to receive it, which is determined by signal to the noise level. However, with multiple readings and matched to the signal detection, also tag signals with power below the noise level can be read. The total power radiated by the reader typically is on the order of 10 mW. For high-speed long-read-range applications, only a fraction of a microwatt is needed at the tag position (RFSAW, 2004). This is the typical power level to which human beings will be exposed when in proximity of SAW tag systems. It is about a hundred times lower than the radiation exposure generated by mobile phones.

RFID systems based on semiconductor chips use an IC to receive and detect the signal sent by the reader, as well as to subsequently decode the signal and generate the response. The functional blocks of a typical IC tag include power accumulation, computation, and communication. The main feature of IC semiconductor tags is that they must include a proper DC power source for correct operation. The so-called 'passive' IC RFID tags that do not carry a battery are obliged to take this power from the RF interrogation signal. The main part of the signal sent by the reader serves for powering the IC and only a small modulation of this signal is for transmission of data. A rectifier circuitry is used to extract a sufficient power from the radio signal. The rectifier converts the signal into DC for storage in a capacitor and, ultimately, for powering the chip. The reading of the tag is performed using a predetermined protocol and is only possible if the necessary DC power level is maintained throughout the entire interrogation cycle. To this end, a minimum critical power of about 100 μW must be received continuously by the tag antenna during the whole time of decoding of the tag's signal (RFSAW, 2004). Below this signal threshold, rectification is not possible. This power restriction is imposed by the physics of semiconductors and thus is fundamental. For SAW tags, on the other hand, which are linear passive devices, no threshold exists. They generate a response at all power levels, usually orders of magnitude lower than what is required for IC tags.

VIII. CONCLUSIONS

In this short review we argued that SAW tags have clear advantages over IC semiconductor RFID devices in many aspects:

- SAW tags practically have an infinite number of codes sufficient for all reasonable applications.
- SAW tags have an incomparably larger reading distance with the same power radiated by the reader, when compared to IC-chip-based tags.
- SAW tags are small, robust, and can operate in harsh environments where IC-based tags fail.
- SAW tag readers using correlation techniques for signal processing can read several SAW tags simultaneously (Hartmann & Claiborne, 2003).
- SAW tags can easily be used as temperature sensors with ID function [30]

To sum up the above arguments, it is evident that the necessary technological tools as well as the necessary infrastructure and prerequisites are available for the development of smart SAW tags based systems. In a different direction, the development of internet offers conditions for efficient transfer of information to and from databases, which in turn is another pre-condition for the efficient use of RFID tags.

SAW tags offer an excellent technical solution. However, to convert this brilliant idea into a multi-billion business, a number of scientific and technological challenges must be solved, and the fabrication cost of reader devices and tags must be decreased drastically.

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REFERENCES

[1] C.S. Hartmann "Future high volume applications of SAW devices," Proceedings of 1985 IEEE Ultrasonics Symposium, vol. 1, pp. 64-73, 1985

[2] See, for example, documents presented on www.rfsaw.com

[3] P. H. Cole and R. Vaughan, "Electronic surveillance system", 1972, U. S. Patent no. 3706094.

[4]. P. A. Nysen, et al., "System for interrogating a passive transponder carrying phase-encoded ..." US Pat. 4725841 - Filed Jun 30, 1983 - X-Cyte, Inc.

[5] V. P. Plessky, S. N. Kondratiev, R. Stierlin, and F. Nyffeler, "SAW tags: New ideas," Proc. IEEE Ultrason. Symp., vol. 1, Nov. 7–10, pp. 117–120. (1995)

[6] L. Reindl, G. Scholl, T. Ostertag, A. Pohl, R. Weigel, „Wireless Remote Identification and Sensing with SAW Devices", Proc. IEEE 1998 MMT/AP International Workshop on Commercial Radio Sensor and Communication Techniques

[7] Reindl, L. M. & Shrena I. M. Wireless measurement of temperature using surface acoustic waves sensors. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 51, (November) pp. 1457-1463, (2004)

[8] Stierlin, R. & Küng R. Process for carrying out a non-contact remote inquiry, U. S. Patent no. 6407695, 2002.

[9] R. Stierlin and al., US patent 6'630'900, 2003

[10] Hartmann, C. S. A global SAW ID tag with large data capacity, *Proceedings of IEEE Ultrasonics Symposium*, pp. 65-69, Münich, Germany, October 2002.

[11] Hartmann, C. S. & Claiborne, L. T. (2003). Anti-collision interrogation pulse focusing system for use with multiple surface acoustic wave identification tags and method of operation thereof, U. S. Patent no. 7084768, 2003.

[12] Hartmann, C. S.; Brown, P. & Bellamy, J. (2004). Design of global SAW RFID tag, *Proceedings of 2nd Int. Symp. Acoustic Wave Devices for Future Mobile Commun. Syst.*, pp. 15-19, Chiba, Japan, March 2004.

[13] Hartmann, C. S. (2005). Surface acoustic wave identification tag having enhanced data content and methods of operation and manufacture thereof, U. S. Patent no. 6966493, 2005.

[14] Hartmann, C. S. & Plessky, V. P. (2007). Single phase unidirectional surface acoustic wave transducer and improved reflectors, U. S. Patent no. 7173360, 2007.

[15] RFSAW, Inc. (2004). The Global SAW tag – a new technical approach to RFID. http://www.rfsaw.com

[16] D.C. Malocha, D. Puccio, D. Gallagher, "Orthogonal frequency
coding for SAW device applications," Proc. IEEE International
Ultrasonics Symposium, 2004, pp. 1082-1085

[17] J. Brungot, L. Hoff, S. Holm, A. Rønnekleiv, DT Wang, et al. - US Patent 7,307,537, 2007

[18] Davies, D. E. N.; Withers, M. J. & Claydon, R. P. Passive coded transponder using an acoustic-surface-wave delay line. *Electronics Letters,* Vol. 11, No. 8, (April, 1975) pp. 163-164, (1975).

[19] Shannon, C. E. A mathematical theory of communication. *The Bell System Technical Journal,* Vol. 27, (1948, July, October) pp. 397-423, 623-656.

[20] Stelzer, A.; Pichler, M.; Scheiblhofer, S. & Schuster, S. Identification of SAW ID-tags using an FSCW interrogation unit and model-based evaluation. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 51, (November) pp. 1412-1420. (2004).

[21] Härmä, S.; Arthur, W. G.; Hartmann, C. S.; Maev, R. G. & Plessky, V. P. (2008). Inline SAW RFID tag using time position and phase encoding. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 55, (August) pp. 1840-1846.

[22] Kuypers, J. H.; Reindl, L. M.; Tanaka, S. & Esashi, H. Maximum accuracy evaluation scheme for wireless

SAW delay-line sensors. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 55, (July 2008) pp. 1640-1652.

[23] Shmaliy, Y.S. Ibarra-Manzano, O. Aridrade-Lucio, J. Rojas-Laguna, R., Approximate estimates of limiting errors of passive wireless SAW sensing with DPM *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* Oct. 2005, Volume: 52, Issue: 10, 1797- 1805.

[24] Härmä, S.; Plessky, V. P.; Hartmann, C. S. & Steichen, W. Z-path SAW RFID tag. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 55, (January) pp. 208-213.

[25] Breed, G. (2005). A summary of FCC rules for ultra wideband communications. *High Frequency Electronics,* Vol. 4, pp. 42-44. (2008).

[26] Ianelli, Z. & Koslar, M., Surface-wave transducer device and identification system with such device, U. S. Patent no. 6788204, 2004.

[27] Reindl, L. & Ruile, W. Programmable reflectors for SAW-ID-tags, *Proceedings of IEEE Ultrasonics Symposium*, pp. 125-130, Baltimore, MD, USA, November 1993.

[28] L Reindl, T Ostertag, W Ruile, CCW Ruppel, … Hybrid SAW-device for a European train control system - 1994 IEEE Ultrasonics Symposium, pp. 175-179.

[29] Reindl, L.; Scholl, G.; Ostertag, T.; Scherr, H.; Wolff, U. & Schmidt, F., Theory and application of passive SAW radio transponders as sensors. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 45, pp. 1281-1292. (1998).

[30] Schmidt, F.; Sczesny, O.; Reindl, L. & Mágori, V. Remote sensing of physical parameters by means of passive surface acoustic wave devices (“ID-tag”), *Proceedings of IEEE Ultrasonics Symposium*, pp. 589-592, Cannes, France, November 1994.

[31] S. Härmä “Surface Acoustic Wave RFID Tags: Ideas, Developments, and Experiments” PhD thesis, http://lib.tkk.fi/Diss/2009/isbn9789512297436/isbn9789512297436.pdf