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DESIGN OF GLOBAL SAW RFID TAG DEVICES

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Abstract - The Global SAW Tag [1] is projected to be a large-volume SAW device application. The modulation method and overall tag data structure are reviewed for a family of proposed RFID devices. Current implementations use a basic group structure that encodes 16 information bits using 4 reflectors chosen from 75 reflector slots. Several groups are placed in-line on a single acoustic track to achieve ID tag devices with capacities up to 256 bits. RFID system requirements for anti-collision, low tag loss and high tag accuracy are presented. A design example for a single group shows that data dependent amplitude and phase errors can be eliminated. The tag reflectors use a unique floating-electrode reflector structure in a single acoustic channel. Diffraction compensation of individual reflector taps is used to eliminate loss and numerous phase and amplitude distortion effects.

I. Data Group Structure

The Global SAW Tag [1] is based on a unique modulation method that combines time overlapped pulse position modulation along with simultaneous phase offsets and with multiple pulses per data group. Figure 1 illustrates the specific data group structure that is used as the core building block for proposed international standards for SAW RFID [7].

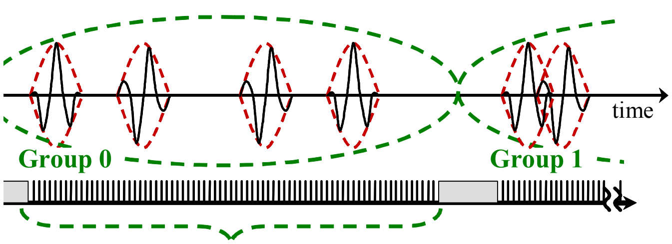

Figure 1: Each 16 bit data group has pulses placed in 4 of 75 slots time of ~3.05 nsec. width, with -64° phase shift per slot. A minimum pulse separation of 12 time slots is enforced to allow detection of individual pulses under the Nyquist criteria. Also, 11 unoccupied slots exist between groups for this same purpose.

The data group structure of Figure 1 was designed to balance a variety of real world RFID system requirements such as operating in the presence of strong interfering signals, minimizing tag cost, enabling robust anti-collision (simultaneous decoding of multiple tags signals that arrive simultaneously), and successfully operating with the limitation that only an ~40 MHz portion of the 83 MHz bandwidth of the 2.45 GHz ISM band may be accessible.

Based on equation 3 of reference 1, the parameters indicated in Figure 1 create a data group with 111,930 unique states. Of these, 65,536 states are chosen to encode 16 bits of data. This excess number of states allows for elimination of undesired pulse patterns (e.g. those that produce strong multi-bounce echoes) and choosing a specific subset that optimizes code orthogonality and data link performance. An encoding/decoding algorithm that maps between a particular 16 bit number and a specific set of 4 pulse positions has been developed [2].

II. Overall Tag Data Structure

The overall tag data structure consists of a number of 16 bit data groups that are separated by 11 empty time slots (see Figure 1). Thus 16 bit, 32 bit, 48 bit, 64 bit, and higher sizes can all be implemented. Sizes up to 256 bits appear feasible. Figure 2 illustrates a 128 bit "tag platform" consisting of 8 data groups.

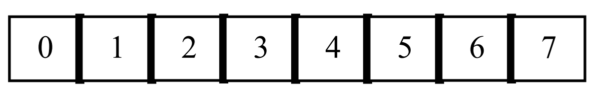

Figure 2: 128 bit tag platform consisting of 8 groups with 75 slots per group plus 11 empty slots between groups for a total of 677 slots

It should be obvious that many other configurations could be used for encoding data onto a Global SAW Tag. One might, for example, allow occupancy of the empty slots between groups without violating the minimum pulse spacing rule used to satisfy the Nyquist criteria.

Reflectors for purposes like temperature sensing, synchronization, version control, etc. can be added ahead or behind the tag platform shown in Figure 2. However, in uses where multiple tag signals collide, this approach is not acceptable because the resulting pulses would generally be in the same fixed positions for all tags and thus be unusable for any of the tags.

III. Anti-collision Requirements

Virtually all high volume RFID applications require the ability to read multiple tags in the reading field at one time. This is only possible if each RFID tag has a unique ID number. One numbering method is the EPC code [3] which contains both an item ID number and a serial number. A unique number is the basis for implementing anti-collision in any RFID technology.

For Global SAW Tags, various combinations of anti-collision methods will be utilized. One of these is spatial whereby the narrow beam widths of 2.45 GHz antennas are used to minimize the number of tags whose signals arrive simultaneously. The gain inherent in narrow beam antennas has the added advantage of increasing reading range. However, since simultaneous return signals will still occur, the signal must be structured in a manner such that the reader can accurately determine the unique identities of the separate tags. Signal separation using matched filtering is the basic method for accomplishing the required signal based anti-collision.

Key elements of signal structure include, a) choice of a signal set with optimized cross correlation for the basic 16 bit group, b) scrambling of tag data to maximize the encoding distance between a collection of tags of identical items, c) multiple levels of error detection, d) an encoded synchronization signal that achieves 32 bit processing gain, and e) other features. One key design choice was the number of bits in the basic data group. The 16 bit size shown in Figure 1 was chosen as a compromise between processing gain and the number of filters needed to implement group by group matched filter processing. The details of the signal structure and anti-collision processing are beyond the scope of this paper.

To accomplish signal based anti-collision, multiple tag data groups are utilized to encode information for synchronization, version number, and one or more error checks. Typically 48 to 64 bits are required for these purposes. Thus, the Global SAW Tag versions of the 64 and 96 bit EPC tags [3] will be implemented using 128 bit and 160 bit tag platforms respectively.

The term "tag platform" was created to describe the un-encoded data capacity of a Global SAW Tag and to distinguish it from the encoded tag data capacity as seen by the end user. Obviously, a tag platform of a given size can be utilized for implementing a wide range of signal structures and end-user sizes.

IV. Reflector Design for Minimum Loss

Since read range is a primary performance criterion of a SAW RFID tag, minimizing insertion loss is a key design issue. Open-circuit aluminum reflector electrodes on 128^{O} $LiNbO_3$ with fundamental frequency mode operation and ~5% h/λ were chosen because, among other reasons, they combine high reflectivity per electrode with low scattering loss into bulk [4], they have low acoustic damping losses and also avoid I^2R resistive losses. The combined losses of such reflectors are sufficiently small such that each reflector only contributes approximately -0.1 dB energy loss (*E)*. Therefore, energy balance for the i^{th} reflector is given as follows.

$$R_i^2 + T_i^2 = E \cong 0.977 \qquad (1)$$

In SAW RFID tag designs, early reflectors are weaker than later reflectors so that a nominally uniform impulse response is achieved. However, in this paper, the amplitude of each pulse will be allowed to differ from the subsequent pulse amplitude by a slope factor *S*. If *L* is the free surface propagation loss between pulses, the reflectivities of adjacent reflectors must obey the following relationship.

$$R_{i+1} T_i^2 L = S R_i \qquad (2)$$

These simultaneous equations are solved to obtain:

$$R_i = 0.5\left[\frac{-S}{R_{i+1}L} + \sqrt{\left(\frac{S}{R_{i+1}L}\right)^2 + 4E}\right] \qquad (3)$$

Reflector strengths can be designed by setting the reflectivity of the final reflector to a value that is determined by the maximum allowed multi-bounce spurious level. Then the reflectivity of all preceding reflectors is determined by equation 3.

Figure 3 shows the reflection loss and individual reflector strengths for three design conditions that range from -13.6 dB slope over the first 5 groups to zero slope across the entire device. These examples show that reflection strength of early groups can be increased without major impact on the reflection loss of the back end groups. This design flexibility can be used to provide added immunity to environmental echoes, to allow choice of convenient reflectivity values for early reflectors, and to minimize error effects.

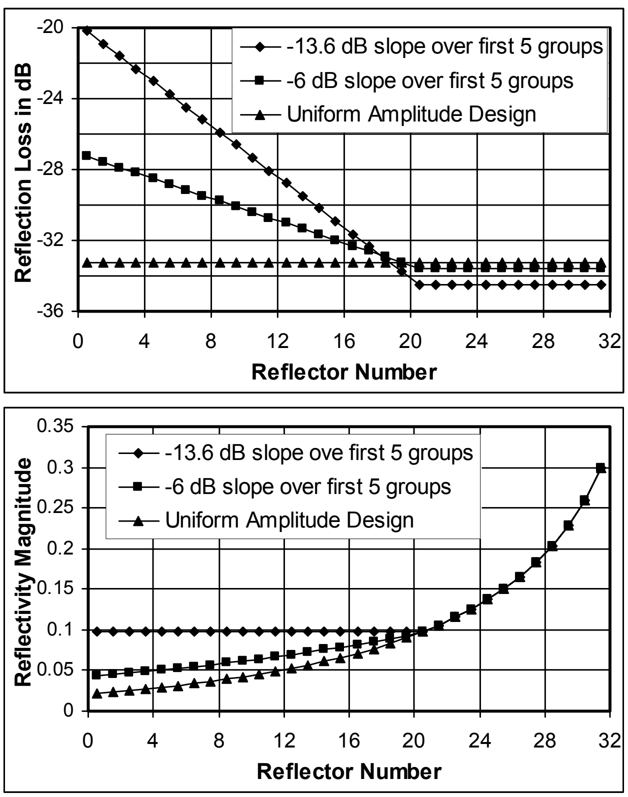

Figure 3: Three single track design variations for a 128 bit Global SAW Tag platform using Equation 3. Top shows reflection loss not including losses from the transducer and pedestal delay. The bottom figure shows individual reflector strengths. Average pulse spacings were assumed for these calculations.

V. Single Group Design Example

This design assumes use of a 2 stage fabrication process in which all 75 possible reflectors in each group are produced and a second encoding stage removes all reflectors except the 4 that are desired. This process inevitably means that both the amplitude and phase associated with a particular slot (see Figure 1) will depend on the encoded data value since the number of occupied slots preceding a particular reflector position is data dependent. Since this effect is unavoidable, the potential errors are removed by developing closed form equations for the amplitude and phase dependency and then using these to calculate correction terms in the tag reader decoding process.

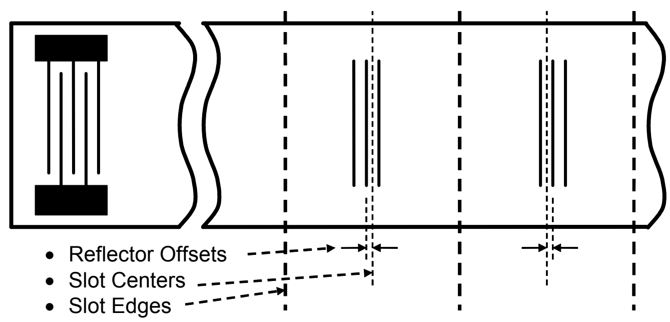

Figure 4: Two slots of an un-encoded Global SAW Tag with 3 open-circuit reflectors per slot and showing the locations of slot edges, slot centers, and reflector offsets as needed to produce desired slot phase shifts.

For simplicity, this paper will consider the design of a single group for which the reflectivity is uniform so that each reflector has the same number of electrodes, N_E, with period, P, and SAW velocity V_E. Since the encoded tag will have a fixed number of active reflectors, N_R, in each group, it is possible to choose the slot width, W, such that the overall time delay of the entire group, T_G, is always correct regardless of the encoded data value.

$$W = \frac{V_{Free}}{2N_{Slots}}\left[T_G - N_R N_E\left(\frac{1}{V_E} - \frac{1}{V_{Free}}\right)\right] \qquad (4)$$

The slot edges and centers shown in Figure 4 are determined by this slot width, W.

Figure 4 also indicates an offset of the reflector positions away from the centers of the time slots. This is needed to produce a reflection phase shift per slot that is consistent with the uniform phase difference between slots, $\Delta\phi$, as required by the Global SAW Tag modulation[1]. The design value, θ_{Ri}, for the reflection phase of the i^{th} is given as follows.

$$\theta_{Ri} = \theta_{R1} + (i-1)\Delta\phi - (i-1)2p\Delta\varphi \qquad (5)$$

In equation 5, p is the probability a given slot is occupied after the device is encoded, and $\Delta\varphi$ is the difference between the single-pass phase shifts of a slot when a slot is occupied as opposed to being empty.

The slot encoding function i_j gives the slot position i of the j^{th} pulse in a particular group. Then the amplitude and phase of any given pulse after the device is encoded is given as follows.

$$A_j = T_{Free}^{2(i_j - j + 1)} T_{Occupied}^{(2j-1)} R \qquad (6)$$

$$\theta_j = \theta_{Ri_j} + (i_j - j + 1)\Delta\varphi \qquad (7)$$

The pulse amplitude, A_j, is referenced to the front edge of the group (i.e. it does not include the loss due to passing through preceding groups etc.). The factors T_{Free} and $T_{Occupied}$ are the single pass transmission factors through an unoccupied and an occupied slot respectively. At 2.45 GHz on 128^O $LiNbO_3$ with a single pass slot width of ~1.5 nsec, $T_{Free} = 0.99776$. $T_{Occupied}$ is determined using the equations of Section IV.

Equation 6 and 7 are closed form expressions for the amplitude and phase dependency on the encoded data values i_j. These can be used to calculate correction terms in the tag reader decoding process thereby eliminating potential amplitude and phase errors.

The design procedure shown above is simplified. In reality, the reflectivity is not always uniform across a single group, and velocity dispersion exists at these frequencies which must also be compensated.

VI. Diffraction Correction

In addition to the various effects discussed above, a SAW RFID device has a long propagation path which leads to well known diffraction effects that perturb the amplitude and phase of the surface wave arriving at a particular reflector. In addition to causing unacceptable phase and amplitude errors in the tag device response, diffraction will also increase insertion losses. Also, the open-circuit reflectors will not function properly because the curved SAW wavefronts will be mismatched to a straight reflector electrode, and, since the incident SAW amplitude is not uniform along the reflector, partial shorting will occur as current will flow along the length of each reflector from areas with high incident wave amplitude to areas of low amplitude or areas with opposite phase.

Rather than abandon the open circuit reflectors, these various potential problems can be solved by using reflectors that are curved to match the incoming wave and by segmenting these open circuit reflectors so that current cannot flow from high amplitude areas to lower amplitude areas. While the design details are beyond the scope of this paper, two diffraction-compensated reflector layouts are shown in Figure 5.

(a) Far Field Reflector

(b) Near Field Reflector

Figure 5: Two diffraction-compensated reflector layouts for a 94 wavelength beamwidth tag device. The x and y axes are distorted by 22:1 for purposes of clarity.

By using diffraction-compensated reflectors, the potential problems of using open circuit reflectors are eliminated, the potential amplitude and phase errors due to diffraction are compensated, and diffraction related insertion loss is largely eliminated. It can be shown that the reflected signal from these reflectors have the proper phase and amplitude distortion such that diffraction effects that occur on the path back to the input transducer create the wavefronts with approximately flat phase front and rectangular amplitude distribution that matches the transducer electrode overlaps. Total diffraction related insertion loss is estimated to be less than -0.4 dB for all reflectors.

VII. Experimental results

Figure 6 shows experimental results from a 128 bit Global SAW Tag platform that has been encoded to implement a 64 bit EPC tag. These tags have been used for field testing the Global SAW Tag system for identifying a variety of products including both liquids and metal objects. Further improvements in tag insertion loss are expected by making use of a unidirectional SAW transducer at 2.45 GHz [5].

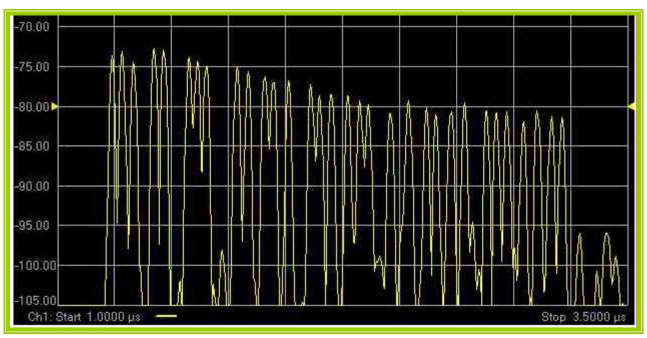

Figure 6: Experimental measurement of a 64 bit EPC Global SAW Tag. The tag is implemented using a 128 bit tag platform and includes encoding for anti-collision, multi-level error detection and other features. Insertion loss for the back end pulses is -53 dB. Vertical scale: 5 dB / division. Horizontal scale 0.25 microseconds per division from 1 to 3.5 microseconds.

VIII. Conclusions

The Global SAW Tag project has grown beyond SAW device R&D to encompass reader design, application engineering, and efforts at creating an international SAW RFID standard. In many applications areas the Global SAW Tag will experience strong competition from IC chip based RFID tags. However, IC chip based RFID has a fundamental problem of having to power the chip from energy received from the tag reader. This significantly limits the read reliability and read range for this competitive technology such that certain market projections predict a 10% market share for SAW RFID by 2007.

[1] C. S. Hartmann, "A Global SAW ID Tag with Large Data Capacity", Proc. 2002 IEEE Ultrasonics Symposium, pp. 63-67.
[2] C. Hartmann and J. Bellamy – to be published
[3] See www.epcglobalinc.org
[4] S. Lehtonen, V.P. Plessky, and M.M. Salomaa, "Short Reflectors Operating at the Fundamental and Second Harmonics on 128^{O} $LiNbO_3$" Proceedings of 2002 IEEE Ultrasonics Symposium, paper 4H-5
[5] S. Lehtonen, V.P. Plessky, C.S. Hartmann, and M.M. Salomaa, "Unidirectional SAW Transducer for GHz Frequencies on 128° $LiNbO_3$", Proceedings of 2003 IEEE Ultrasonics Symposium, paper 5H-4
[6] L. Reindl and W. Ruile, "Programmable Reflectors for SAW-ID-Tags", Proceedings of 1993 IEEE Ultrasonics Symposium, pp 125-130
[7] The Auto ID Center's hardware action group has created a candidate standard for "Alternative Technology Class 1 EPC Tags" based on the Global SAW Tag. Public release of that document will only occur after a final approval by EPCglobal, Inc.