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A Global SAW ID Tag with Large Data Capacity

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Abstract - The Global SAW Tag uses a recently-invented digital modulation based on simultaneous time position and phase shifting. A unique feature of this tag is that it satisfies global RFID requirements using the international 2.44 GHz ISM band. Precision amplitude and phase weighting of reflectors and accurate control of parasitic effects is critical to implementing this device. This tag has significantly more data bits, lower insertion loss, and smaller die area (i.e. lower cost) than previous SAW tags. These improvements eliminate the shortcomings that have previously limited the market for SAW RFID (radio frequency identification). A 2.44 GHz fundamental mode tag on 128^{O} $LiNbO_3$ with 64-bit data capacity plus 16-bit error detection coding is described.

I. INTRODUCTION

Identification devices that use radio waves originated in World War II with IFF (identification friend or foe) transponders for allied aircraft. The use of a coded SAW device as a passive ID tag dates to the early 1970's [1]. In the intervening 30 years, both commercial firms and university research have produced many variants of the SAW RFID tag [2].

While most of these tags were a technical success, SAW RFID tags had limited commercial success primarily because SAW tags could only implement a limited set of unique ID numbers. For example, customers will not buy millions of ID tags if only ~100,000 unique numbers are available. The Global SAW ID Tag solves this and other problems.

II. CURRENT MARKET

Studies have shown that US$ trillions ($ 10^{12}) are lost every year due to products that are lost, stolen, misrouted, over/under stocked, out-of-date, etc. Since the mid 1990's, demand has been growing for a new automatic identification technology to solve these problems. Repeated attempts to use bar coding for this purpose generally failed. The problems with bar codes are that they are not "automatic" (human operators are generally required), and the reliability of line-of-sight bar code reading is unacceptable due to tag damage, surface dirt, tag misorientation, and other effects such as tags being hidden from view.

A consensus has emerged that an advanced version of radio frequency identification (RFID) is the only approach that can implement the required automatic identification (Auto ID) technology. To foster that development, the Auto ID Center, a research consortium, was formed at MIT by large potential users, standards organizations, and technology companies (www.autoidcenter.org). This center has proposed an electronic product code [3] (EPC), which is an innovative ID tag numbering system that is capable of providing a globally unique ID number for every item in the world. Two EPC types have been defined, 96 bit and 64 bit [3].

The Auto ID Center has also recommended that a set of standard RFID tags be developed which are a) read-only (i.e. contain only the EPC number), b) are passive (i.e. no batteries), c) are legal in all countries, d) have robust read range, and e) have a very low cost. This set of recommendations by the Auto ID Center has drawn wide-spread support from around the world. The estimated market demands for such tags range from 10 Billion (10^{10}) to one trillion (10^{12}) units per year depending on tag price and performance. The Global SAW Tag (GOST) that is introduced in this paper is ideally suited to fill these needs.

III. EXISTING SAW RFID DEVICES

Figure 1 illustrates a typical configuration of a SAW RFID tag. Generally it is a one-port device consisting of an interdigital transducer (IDT) and a series of acoustic reflector taps. The IDT is directly connected to the tag's antenna which both receives the interrogation signal from a reader and radiates the reply signal generated by the SAW tag. The reflector taps have modest reflectivity and are placed on the surface in a manner that encodes the tag's data using either time delay, amplitude, phase and/or other variables. Each reflector creates a pulse in the SAW tag's impulse response. A SAW mode with low wave dispersion and with good energy trapping in free surface regions (such as the Rayleigh-type surface wave) is generally used. Also, since SAW tags generally have wide bandwidth and operate in the GHz frequency range, strong piezoelectric coupling and low propagation loss are desirable.

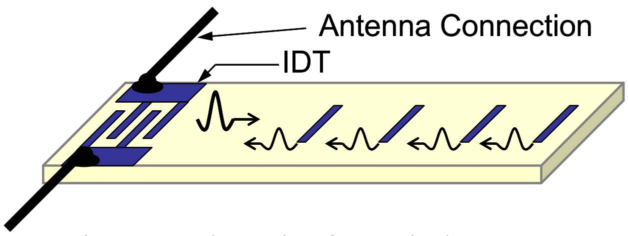

Figure 1: Schematic of a Typical SAW Tag

Numerous SAW tag structures have been previously proposed such as multiple acoustic tracks, folded acoustic paths, multiple device ports, IDTs used as phase/amplitude variable reflectors, unidirectional input transducers, transversal IDTs used to implement device encoding and many others. It will be evident that such variations can be applied to the Global SAW Tag described later.

Figure 2 illustrates the pulse position encoding method used in a commercially available system [5]. In this case, a start pulse is used to provide timing synchronization for the remaining data pulses. Each data pulse can have one of 4 possible time positions and thus 2 data bits are encoded for each pulse. Pulse exclusion regions exist between data groups.

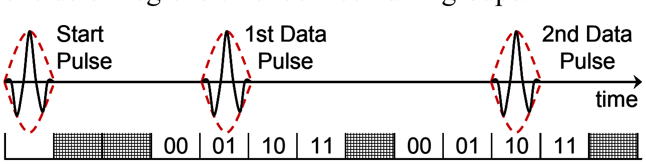

Figure 2: Data Encoding for an Existing SAW Tag

Another type of SAW tag uses on/off pulse encoding in which each possible pulse position encodes one data bit. In this case, exclusion regions are not used. However, the widths of pulse slots are typically increased by a factor of ~2 to ensure clean separation since adjacent pulse positions can be occupied. Overall, pulse position encoding and on/off encoding achieve similar data density per unit time. However, pulse position encoding has the advantage of 50% fewer data pulses which means 50% fewer reflectors on the SAW tag and substantially improves tag insertion loss. It has the further advantage of using a fixed number of reflectors which a) improves data detection (one and only one pulse exists in each data group), and b) enables uniform amplitude of data pulses. Since each reflector slightly reduces the amplitude of the rightward directed signal shown in Figure 1, a fixed number of reflectors means that signal pulses that originate from later reflectors always have the same amplitude.

A characteristic of data encoding in existing SAW tags is the spacing of allowed pulse positions that is roughly equal to the time width of the pulses (approximately $1/\Delta F$ where ΔF is the bandwidth of the overall system). In contrast, the reflectors used in these devices have a spatial extent that is much smaller than the equivalent time length of the pulses due to a very wide bandwidth compared to ΔF. Great interest exists in close reflector spacing to increase the SAW tag's data capacity; however, the resulting small pulse spacing would be difficult to decode with existing modulation methods since overlap between adjacent pulse positions could exceed 90%.

IV. GLOBAL SAW TAG (GOST)

The core difference between the Global SAW Tag and existing SAW tags is a new class of data encoding methods with the properties of much higher data density and a higher number of data bits for each signal pulse. There are numerous physical implementations that are possible for the Global SAW Tag which are consistent with variations described earlier in Section III.

Figure 3 shows an example of data encoding as used in the Global SAW Tag. Several differences are evident as compared to the data encoding of existing SAW tags as shown in Figure 2 as follows:

- Many more pulse time positions are allowed;
- Time steps are much smaller than pulse width;
- A phase step accompanies each small time step;
- Two or more pulses are used per group; and
- While pulse overlap is allowed, spacing between pulses is sufficient to satisfy the Nyquist criteria.

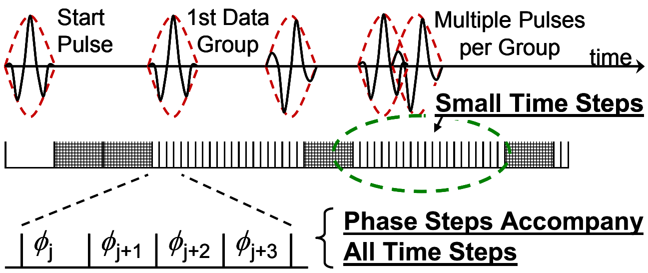

Figure 3: Global SAW Tag Data Encoding Example

The impulse response $h(t)$ for this tag can be expressed as a sum of terms that depend on A_j, the amplitude of each pulse; on $E_j(t)$, the envelope of each pulse; on τ_j, the time delay to the center of each pulse; on ω_j, the radian center frequency of each pulse; and on θ_j, the RF phase of each pulse.

$$h(t) = \sum_{j=0}^{N-1} A_j E_j(t-\tau_j)\ \sin(\omega_j(t-\tau_j)+\theta_j) \qquad (1)$$

The examples discussed herein assume that certain variables are independent of the index j, such that $A_j = A$; $E_j(t) = E(t)$; and $\omega_j = \omega_0$. Also, the time step, τ_{j+1} - τ_j, is chosen to be much smaller than the time width of the envelope, $E(t)$. However, to satisfy the Nyquist criteria, a rule for the minimum allowed spacing between pulses should be enforced such that the phase at the peak of any given pulse will not be unduly distorted by overlap from a neighboring pulse.

The new modulation method used in the Global SAW Tag is named TOPPS (Time Overlapped pulse Position with simultaneous PhaSe offset modulation). TOPPS is uniquely suited to encoding of a transversal tapped delay line SAW device. A_j corresponds to the strength of a tap, τ_j, corresponds to the time position of a tap, and θ_j, corresponds to the RF phase of the tap. If the device taps are sufficiently wide-band (i.e. have a small time extent) then each tap is physically distinct from its neighbors allowing easy device fabrication. The pulse envelope, $E_j(t)$, has a much narrower bandwidth than the individual taps (and thus a larger time extent). It is primarily determined by the rf spectrum shape of the waveform used by the tag reader multiplied by the frequency response of the input IDT.

The bottom of Figure 3 shows the phase of time slots as ϕ_j, which is the baseband phase of each pulse. This baseband phase is of primary importance for tag design and subsequent data decoding. It is given by:

$$\phi_j = \theta_j - \omega_0 \tau_j \qquad (2)$$

Figure 4 shows simulated Global SAW Tag pulses for the cases where a) the position 1 reflector tap is active (at top of figure) and b) the position 2 reflector tap is active (at bottom of figure). In this particular case, the rf reflector phases, θ_1 and θ_2, are identical at 90^O. The desired 64^O baseband phase shift between these pulses is achieved by choosing the time step such that ω_0*(τ_2 - τ_1) equals 64^O.

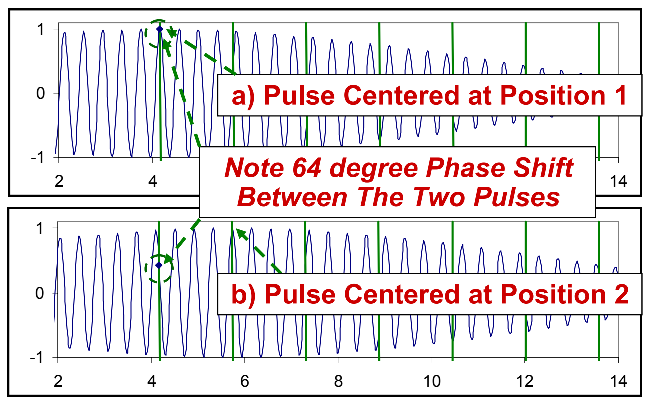

Figure 4: Phase Shift Between Two Adjacent Taps

V. PERFORMANCE METRICS

The Global SAW Tag achieves reliable data decoding despite the fact that the time steps, τ_j, are much smaller than the time width of the pulse envelope $E(t)$. As will be illustrated later, reliable decoding is achieved because the detection error distance between neighboring states is substantially enhanced by means of suitable phase detection.

The number of states N, that are achieved by one pulse data group (see Figure 3), depends on L, the number of time slots in the pulse data group; on M, the number of pulses in that data group; and on K, the minimum number of empty slots that must exist between pulses to satisfy the Nyquist criteria.

$$N = \frac{(L-(M-1)*K)!}{(L-(M-1)*K-M)!M!} \qquad (3)$$

The subject of finding optimum values for the above variables is outside the scope of this paper. However, some important metrics to be considered during optimization include (a) the number of data bits, B; (b) the bit density, D; (c) the pulse efficiency, E; (d) the pulse separation factor, S; and (e) the figure of merit, H, a measure of overall performance.

$$B = \text{int}(\log_2(N)) \quad \text{(bits)} \tag{4}$$

$$D = B/(\Delta t * (L + K))/\Delta F \quad \text{(bits/sec/Hz)} \tag{5}$$

$$E = B/M \quad \text{(bits/pulse)} \tag{6}$$

$$S = \Delta F * \Delta t * (1 + K), \qquad S \geq 1 \tag{7}$$

$$H = D * E \tag{8}$$

In the above equations, Δt is the time length of a slot, ΔF is the system bandwidth, $\Delta T = \Delta t*(L+K)$ is the total time length of a group, and $\Delta t*(1+K)$ is the minimum allowed separation between two pulses.

The separation factor, S, is important for data decoding. Reliable decoding of Global SAW Tag signals requires that near the peak of any data pulse, the phase of that pulse should be relatively undisturbed due to overlap from neighboring pulses. In an ideal system at S = 1, neighboring pulses with minimum spacing would just begin to overlap the peak of a given pulse. However, S will generally be greater than 1 because practical systems (a) are not "ideal", (b) will likely use spectrum shaping to reduce time sidelobes (which increases S), and (c) need reasonable timing error margins for demodulation.

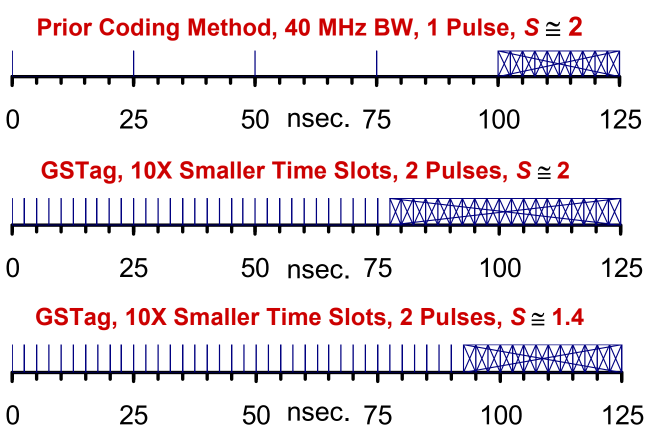

Figure 5: Prior Coding vs. GOST Coding Groups

Figure 5 shows three different pulse groups for comparing the prior SAW tag encoding (Figure 2) to two variants of Global SAW Tag (GOST) encoding. Table 1 gives the corresponding numerical values.

Table 1: Comparison of Prior SAW Tag and GOST

Parameter	Prior	GOST #1	GOST #2
ΔF	40 MHz	40 MHz	40 MHz
ΔT	125 nsec	125 nsec	125 nsec
Δt	25 nsec	2.5 nsec	2.5 nsec
S (separation)	2	2	1.4
L (slots)	4	31	37
M (pulses)	1	2	2
K (skip)	-	19	13
N (states)	4	66	276
B (bits)	2	6	8
E (efficiency)	2	3	4
D (density)	0.4	1.2	1.6
H (merit)	0.8	3.6	6.4

In Table 1, all groups have the same total time length ΔT and bandwidth ΔF. The separation factor is very conservative (S = 2) in the first two cases, and has a more realistic value (S = 1.4) in the third case. GOST #2 improves E, bits per pulse, by 2x and also improves D, bit density, by 4x. Both are quite dramatic because they affect the exponent when calculating the number of unique tag ID numbers. For example, a modest sized SAW tag device might have a coded length of 1 μsec which corresponds to eight of the above groups. For an existing SAW tag this would result in $6.5*10^4$ unique tag IDs (16 bits) while the same size GOST #2 device would have **$1.8*10^{19}$ unique tag IDs numbers!**

VI. EXPERMENTAL RESULTS

Figure 6 shows measured performance of a Global SAW Tag device using fundamental mode operation centered at 2.44 GHz. This device uses spectral weighting to reduce time sidelobes of the pulses and has S = 1.2. Part a) of the figure shows the amplitude of the received signal envelope when measured using a 70 MHz bandwidth system (the legal bandwidth is 80 MHz). Individual pulses cannot be clearly separated in this case. Part b) of the figure shows the received signal envelope when

a) Amplitude of Reply Signal Using 70 MHz Bandwidth

b) Amplitude of Reply Signal Using 200 MHz Bandwidth

c) Output of Synchronized Phase Detector Using 70 MHz Bandwidth Signal (shown with envelope)

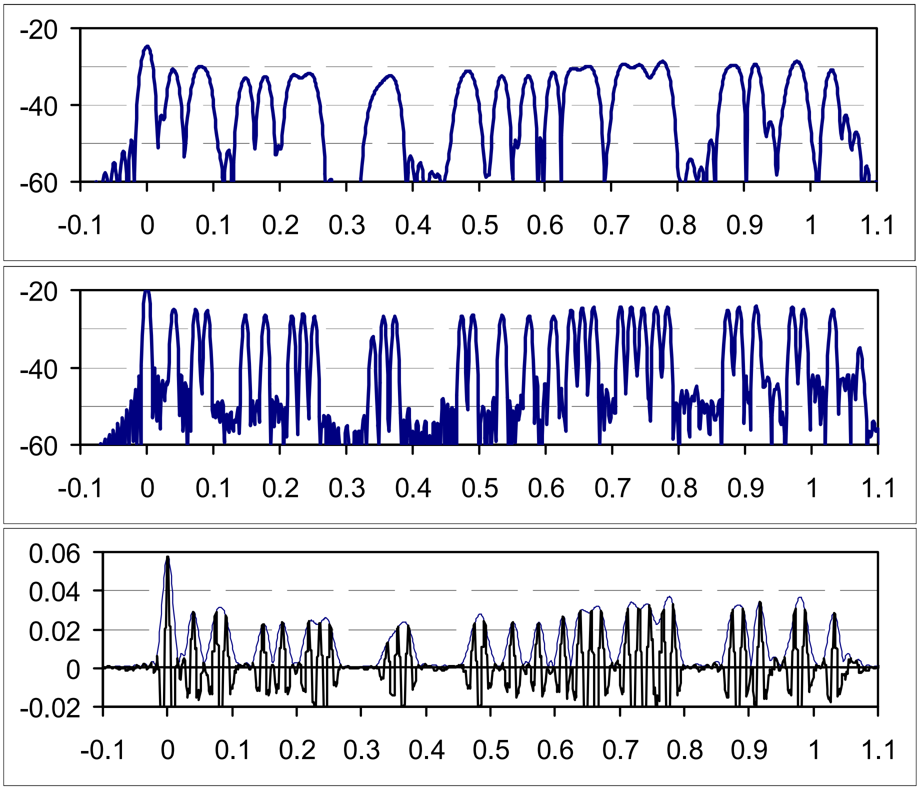

Figure 6: Pulse Response from 2.44 GHz Global SAW Tag with Pulses for Start, Stop, Synchronization, 64 Data Bits, and 16 Bit Error Detection. Uses Fundamental Mode Design on 128^O $LiNbO_3$

measured using a 200 MHz bandwidth system (only legal for lab testing). Part c) of this figure shows the output of a synchronized phase detector whose design details will be presented in a later publication.

From Figure 6b, it is evident that the start pulse is designed to be 6 dB stronger than the remaining pulses. The amplitudes of the remaining pulses are uniform within a 3 dB range except for the 10^{th} pulse which has slight damage to the reflector.

The output peaks from the phase detector shown in Figure 6c are much narrower than the peaks in Figure 6b in spite of using the narrower 70 MHz bandwidth. In fact, the pulse widths in Figure 6b are still too wide to achieve an acceptable detection error distance. In contrast, the pulses in Figure 6c lead to robust discrimination of the very narrow time slots that are being used.

VII. CONCLUSIONS

A new Global SAW Tag (GOST) has been presented that achieves large data capacity and robust performance by use of the new TOPPS modulation. GOST is the only low-cost large-reading-range RFID tag technology that is legal for Global operation and satisfies the requirements of the Auto ID Center [4]. GOST devices are ideally suited to serve emerging global markets for automatic identification systems.

VIII. REFERENCES

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