Cordless Batteryless Wheel Mouse Application Utilizing Radio Requestable SAW Devices in Combination with the Giant Magneto-Impedance Effect

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***Abstract*—Surface acoustic wave devices for wireless identification (ID) systems, the so-called ID tags, can be turned into novel sensor elements (transponders) for impedance sensors by making use of magnetic-field variations caused by the wheel rotation and key-click functionality of a personal computer (PC) mouse. This kind of sensors do not need any power supply and may be interrogated wirelessly. Interdigital transducers are used as loadable reflectors, while another fixed reflector is used as reference to compensate cross sensitivity for temperature, mechanical stress, etc. The load of the reflectors influences amplitude and phase of the reflected wave. The load's impedance is changed utilizing the giant magneto-impedance (GMI) effect in a 30-μm-diameter amorphous FeCoSiNd wire of zero magnetostriciton. The measurand, represented by the PC-mouse key clicks and wheel rotation, influences a magnetic field, which varies the impedance of the GMI wire. Consequently, the load of the reflector influences the reflected acoustic wave and the response signal of the radio sensor. The operating principle of such a magnetic-field sensor is discussed, and the tuning for an application in a passive and cordless PC mouse is presented.**

***Index Terms*—Amorphous FeCoSiBNd wire, cordless and batteryless mouse, giant magneto-impedance effect, magnetic-field sensor, surface acoustic wave sensors, wireless sensing.**

I. Introduction

MOST wireless personal computer (PC) mice and other sensor units are battery operated and contain active semiconductor circuits. Others are powered by an inductive link or by a strong RF carrier signal. The alternating voltage received is rectified and used for power supply.

This paper presents the concept of a cordless and batteryless PC-mouse solution opening new perspectives concerning practicability and reliability.

In recent years, reflective surface acoustic wave (SAW) devices have been introduced as passive radio requestable sensors [1], [2]. Here, we present a new generation of passive SAW sensors, based on n-port SAW devices, utilizing the dependency of the acoustic reflectivity from the electrical impedance of the according port. Conventional sensors (i.e., giant magneto-impedance (GMI) wire) with varying impedance can be read out wirelessly by utilizing SAW reflective delay lines (identification (ID) tags) as transponders. For this application, interdigital transducers (IDTs) of the ID tag, electrically loaded by an external sensor (GMI wire), are used as reflectors. The physical quantity to be measured (PC-mouse key click and wheel rotation) yields a variation of the magnetic field applied and, consequently, influences the load impedance. This changes the acoustic reflection and transmission properties of the IDT and, consequently, modulates an individual part of the sensor response. In Section II, the principle of the passive SAW transponder, as well as simulations, are presented, while Section III shows the theory of the GMI effect. Results of our experiments and the principle of how wheel rotation and key-clicking activity effects the magnetic field applied is then presented in Sections IV and V.

Further, a small-size low-cost interrogation system required for this sensor application is introduced in Section VI.

II. Radio-Requestable Five-Port SAW Transponder

Recently, the applicability of passive SAW devices for remote sensing has been proposed [1], [2]. The new SAW components focused here employ one interdigital transducer (IDT1), connected to an antenna, one IDT operating as a fixed reflector (IDT2), and at least one other IDT (IDT3) loaded by an external impedance Z. Fig. 1 sketches the structure of this impedance-loaded delay-line sensor.

Changing the impedance Z yields a change of the response from IDT3 in magnitude and phase. A compensation of the radio channel influence is done by differential measurement between the response signals from IDT2 and IDT3. In [3], sensor applications for measuring distance, light, pressure, etc. are presented.

An IDT is a three-port device with one electrical port, with the voltage u and current i; and two acoustical ports, with the received waves a_1 and a_2 and the launched waves b_1 and b_2 (see Fig. 2).

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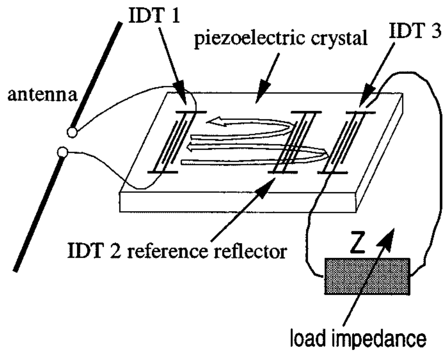

Fig. 1. Schematic layout of a passive SAW device connected to an external impedance.

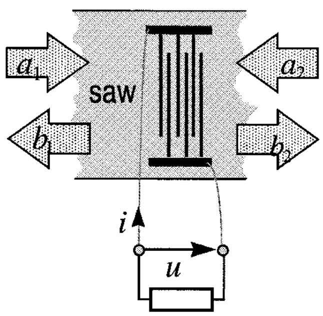

Fig. 2. Three-port model of an IDT.

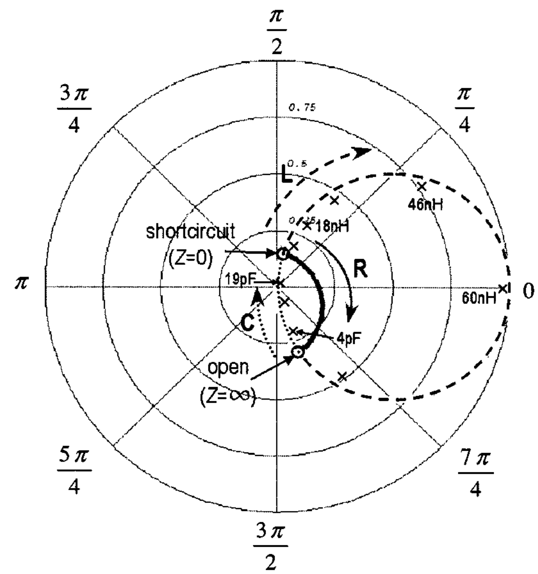

Fig. 3. Polar diagram of the acoustic reflection coefficient P_{11} as function of the external impedance Z (broken line: inductive, dotted line: capacitive, full line: resistive).

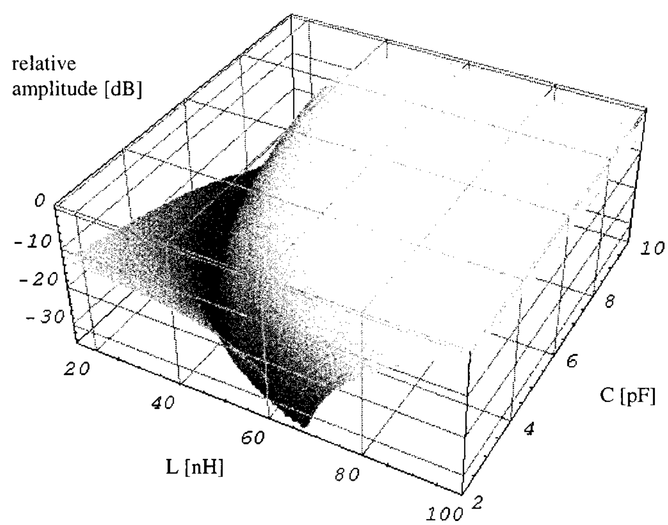

Fig. 4. Amplitude of the reflected impulse versus capacitive and inductive load.

The acoustic reflectivity P_{11} of IDT3 as a function of the complex termination impedance Z at its electrical port is given in the well-known P-matrix formalism [4]

$$P_{11}(Z_{\text{load}}) = P_{11}^{sc} + 2\frac{P_{13}^2}{P_{33} + \frac{1}{Z}}. \tag{1}$$

In (1), P_{11}^{sc} is the acoustic reflection coefficient of the short-circuited IDT, and it is approximately zero for the split-finger IDT applied. P_{33} is the electrical admittance of the IDT, and P_{13} the electroacoustic coupling factor. The impedance Z represents the circuit electrically connected to the IDT. With (1), the acoustic reflectivity only depends on constants and the external impedance.

The electrical load can be interpreted as a serial circuit consisting of a resistive, inductive, or capacitive part Z in series with the inductance of the bonding and connecting wires. Fig. 3 shows an example of the complex acoustic reflectivity of a split-finger IDT as a function of the external impedance part Z in a polar plot. The graphs represent the inductive (broken line), capacitive (dotted line), and resistive (full line) component of Z separately. Additionally, some measured points are shown, proving the good correspondence of theory and experimental results. The smaller the bonding inductance, the further the shortcut point moves toward the origin. The open point is determined by the IDT of the SAW device by P_{13} and P_{33}, respectively. As shown in Fig. 3 and (1), the external load impedance modulates the reflected RF impulse in magnitude and phase. In order to achieve a maximum resolution of approximately 5% for the PC-mouse application, a discrimination only of the amplitude is sufficient. In Fig. 4, the change of magnitude of the reflected impulse versus the parameters of the external serial circuit is shown.

For the PC mouse, a passive SAW transponder with four staggered, impedance loaded (GMI wire) reflectors (Fig. 5) can be used. IDT3 and IDT4 are used to detect the sensitive wheel rotations related to the horizontal PC-mouse movements, while IDT5 (loaded with Z3) is used to implement the wheel rotation functionality (scroll-bar movements). The three key-click activities are detected utilizing IDT6. The signal reflected by the reference reflector (IDT2) is compared in amplitude with that from the IDTs connected to the external sensors (GMI wires). Using staggered reflectors with different distances to IDT1 guaranties high isolation (time separation) between the different sensor tasks. In case the loaded reflectors are placed in line, the impedance-dependent acoustic transmission

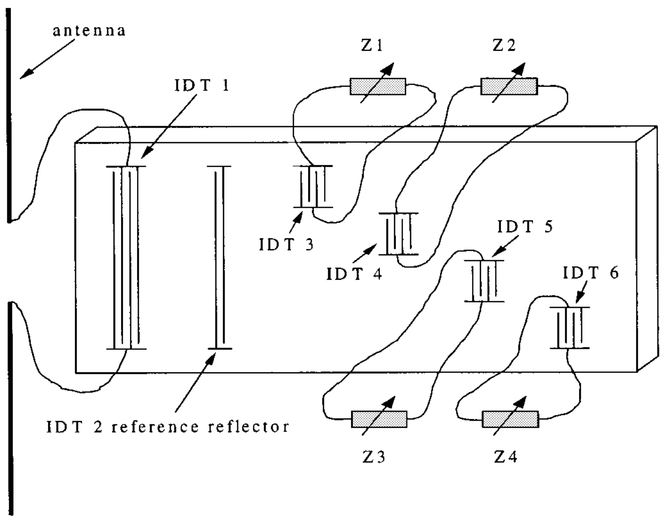

Fig. 5. Schematic layout of a five-port SAW transponder with external impedance terminations.

coefficient P_{21} of one IDT would influence the reflected RF impulse of the following IDT in magnitude and phase.

Depending on the received noise level, the above resolution stated can be achieved. An estimation of the resulting error for different types of error sources is comprehensively summarized in [5].

III. GMI Effect

The impedance of a high-permeability element sensitively changes with an external (quasi-static) field due to the skin effect in a high-frequency current application. This GMI effect [6], [7] shows an extremely high impedance ratio of 100%∼1200%/mT in zero-magnetostrictive amorphous wires.

Another important feature of the GMI element is its independence of the demagnetizing field with respect to the external field. This feature allows the construction of a microscale sensor without decreasing the field-detection sensitivity due to circumferential magnetization with the element current [8]. Quick response is also an advantage of the GMI effect due to the RF current magnetization, which works as a carrier of the amplitude-modulation behavior.

Depending on the frequency $f = \omega/2\pi$, the impedance Z is the ratio of complex ac voltage U to complex ac current I. In a ferromagnetic wire (with radius a and length l and for $\delta \ll a$), [7] it is expressed as

$$Z = R_{\mathrm{dc}}\frac{a}{2\delta} + j\omega L_i\frac{2\delta}{a} = \frac{aR_{\mathrm{dc}}}{2\sqrt{2\rho}}(1+j)\sqrt{\omega\mu} \qquad (2)$$

where ρ is the bulk resistivity, $\delta = \sqrt{2\rho/\omega\mu}$ is the skin depth, $R_{\mathrm{dc}} = \rho l/\pi a^2$ is the dc resistance, $L_i = \mu l/8\pi$ is the internal inductance, $\mu = \mu_{\mathrm{dc}}/(1+jf_r/f)$ is the circumferential permeability, and fr is the domain-wall relaxation frequency.

IV. GMI-Wire Loaded SAW Transponder

For maximum dynamic and sensor resolution, it is necessary that the external circuit is adjusted to achieve resonance with

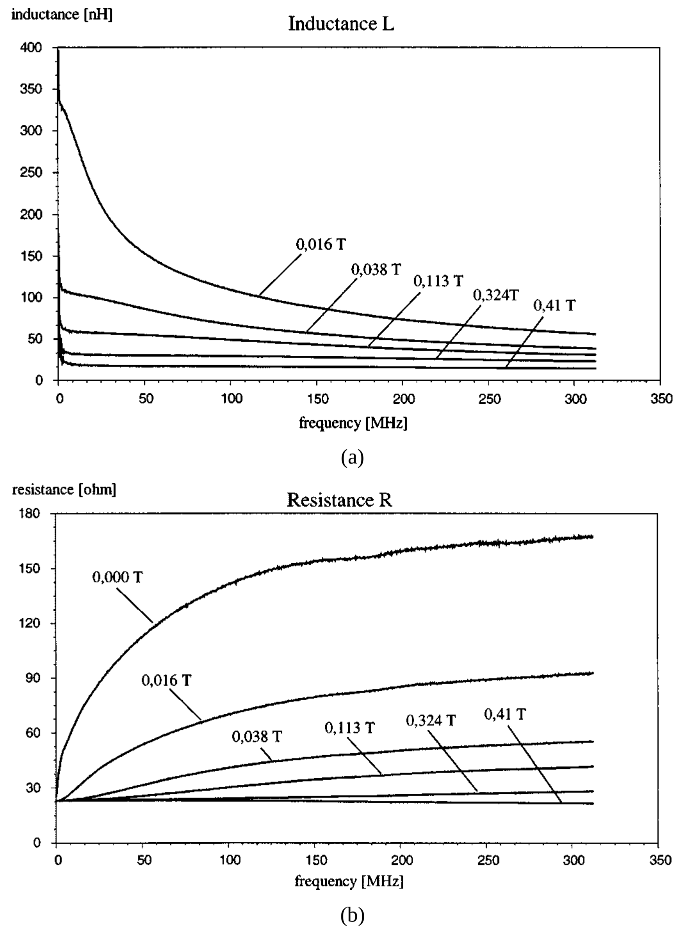

Fig. 6. Resistance and inductance of a GMI wire versus magnetic-field strength.

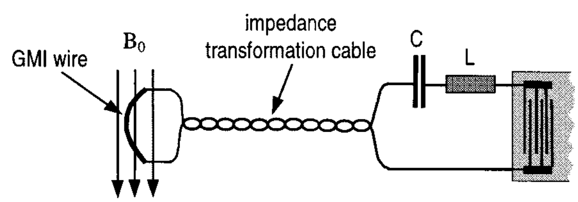

Fig. 7. Matching network for maximum dynamic range.

the transducer's capacitance. This adjustment reflects the locations of the minimums in Fig. 4, also representing the short-circuit point in Fig. 3. Tuning this resonance for, e.g., one octave in frequency by applying a magnetic field to the GMI sensor, yields sufficient effect for a radio-request readout [9]. Passive radio-requestable sensors can be built. In Fig. 6, the variation of resistance and inductance of a GMI wire versus frequency is shown. The system investigated operates in one of the industrial–scientific–medical (ISM) frequency bands at 433.92 MHz. Therefore, the variation of the inductance is between 20 and approximately 100 nH for a magnetic field between 0 and 0.4 T. Due to the low-impedance range of the GMI wire and its high resistive component (Fig. 6) it is necessary to find a matching network for maximum dynamic of the reflectivity of IDT3 to IDT6. Fig. 7 shows the best suited solution with $C = 7$ pF, $L = 25$ nH, and the length of the impedance transformation cable of 1.6 rad (approx. 11.7 cm). The achieved dynamic range

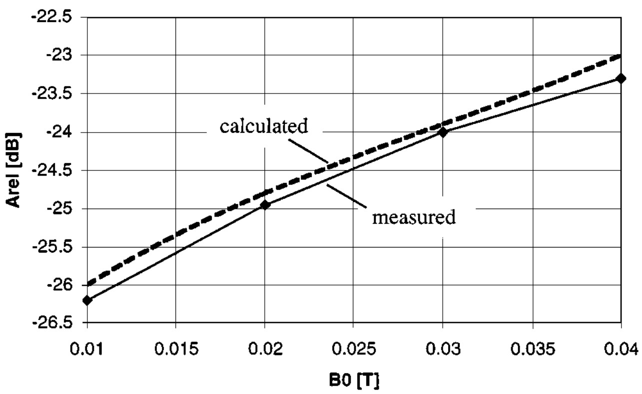

Fig. 8. Amplitude of the impedance-affected reflection relative to the reference reflection.

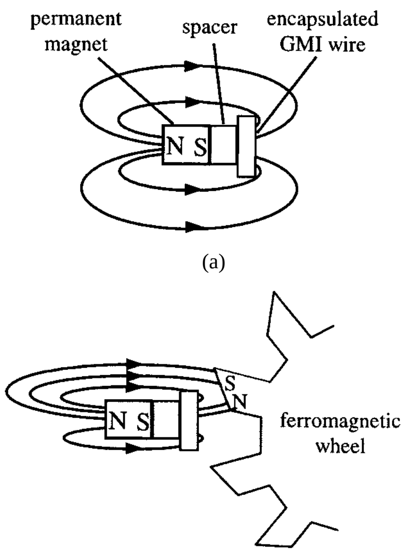

Fig. 9. Sensor configuration for detecting wheel rotation in magnitude and direction.

is about 4 dB, calculated and measured results of the amplitude of the impedance-affected reflection IDT relative to the reference reflector IDT ($A_{\rm rel}$) versus the magnetic field applied (B_0, see Fig. 7) are shown in Fig. 8. Considering different matching network cables of different lengths can be applied.

V. PC-Mouse Sensor Design

In order to detect the wheel rotation in magnitude and direction, a biasing magnet is used to magnetize a ferromagnetic wheel (Fig. 9). The GMI wire detects the combined magnetic field from the wheel and the biasing permanent magnet, which is mounted on top of the sensor with its magnetic axis perpendicular to the sensitive axis of the GMI wire. The teeth of the wheel have a nonsymmetrically (saw-like teeth) surface, influencing the combined field in a nonsymmetrical way depending on the direction of the wheel rotation. Consequently, this construction generates a saw-like teeth amplitude variation of the reflected RF signal, allowing to detect magnitude and direction of the wheel rotation.

The resolution to detect the magnitude of the wheel rotation is mainly limited by the dimensions of the GMI wire. With the 30-μm-diameter amorphous FeCoSiBNd wire we used, the resolution can be assumed to be a few tenths of a millimeter.

The key-click activity is simply detected using three GMI sensors in parallel connected to IDT6. Each GMI wire is influenced by the magnetic field of a single permanent magnet associated to each a key. The clicking key causes the relevant magnet to increase the distance to the associated GMI wire, consequently, decreasing the magnetic field picked up by the sensor. The magnetic field of each permanent magnet is different, allowing to detect which key or combination of keys is currently active.

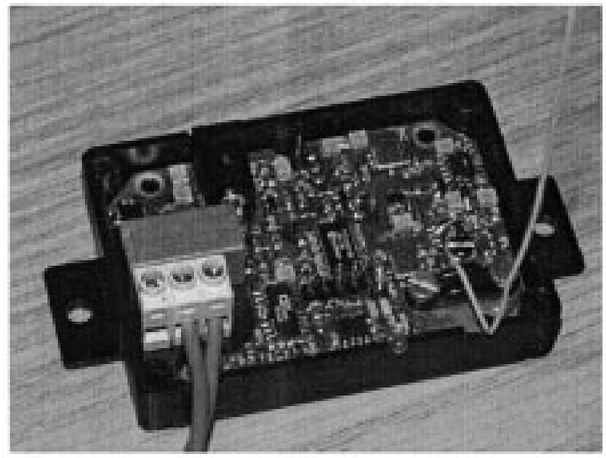

Fig. 10. Interrogation system in opened housing.

VI. Low-Cost Interrogation System

This application requires a small-size and low-cost interrogation system. In order to satisfy these requirements, we developed an optimized RF unit capable of detecting the response signal. This contains information about the propagation and reflection properties of the SAW affected by the measurand.

The evaluation unit has to detect these signals and to evaluate the magnitude for further post data processing [10]. It contains a transmit/receive unit in order to transmit an RF electromagnetic request signal to the SAW transponder via the radio channel.

An RF burst (433.92 MHz) with a duration of approximately 1 μs is generated using a separate mixing unit. Therefore, the clock signal (16 MHz) of the programmable μ Processor (PIC16C73B) is multiplied with a stable continuous wave (CW) signal generated from a SAW Colpitts Oscillator (418 MHz). In order to avoid any crosstalk from the RF signal generation to the receiver unit during the time the sensor signal is received, the mixer is only activated during the time the burst is generated (1 μs).

Utilizing a standardized from stock devices only, a reliable low-cost radio interrogation system has been developed. Fig. 10 presents a photograph of this built interrogation system in an enclosure of 7 cm $\times$ 5 cm $\times$ 2.6 cm.

Concerning the antenna employed for both sides, the interrogation and the passive PC mouse, a $\lambda/4$ patch antenna was chosen. The use of this antenna is a good compromise of small size in contrast to gain and efficiency.

VII. Conclusion

SAW transponders have been developed to operate as reliable passive cordless interrogable sensors without the need of a battery, but almost unlimited lifetime. The combination of the new SAW transponder with a GMI wire as an external sensor result in an excellent quick-response microsized magnetic-field sensor.

The sensing of all PC-mouse functionalities is covered using only one SAW transponder with four impedance-loaded IDTs. For high reliable and robust application, this alliance of the GMI effect and SAW devices offers new perspectives in easy handling man–machine interface units.

A state-of-the-art interrogation system is introduced, based on the use of inexpensive components and avoiding any manual tuning.

The next step of investigation will be the use of SAW transponder operating in the European ISM band at 2.4 GHz. This will offer the use of antennas with higher gain and efficiency, increasing the maximum interrogation distance.

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In 1974, he became a Professor of electronics at TU, where he has been involved with microwave measurements of the acoustoelectric effect, and where he invited the acoustic charge transport devices in 1971. Since 1976, his group has been active in SAW research and spread-spectrum applications. Since 1981, there has been a close cooperation with Siemens Corporate Research Laboratories, Munich, Germany, which lead to a leading position in SAW design and fabrication, and made possible the experimental application of SAW devices for new applications in Vienna. Among these is the production of the first spread-spectrum systems in Austrian industry. He has authored and co-authored approximately 80 publications and one book and holds several patents.

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