Passive resonant sensors: trends and future prospects

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***Abstract*— Sensors based on "resonance phenomenon" span a broad spectrum of important current applications including detection of biological and chemical agents, and measurements of physical quantities. Resonance phenomena occur with all types of waves: electromagnetic, optic, and acoustic. This review reports about the most recent advances in the design and applications of resonant "passive" sensors, i.e. resonant sensors able to operate with a distant power source and/or able to communicate with a distant transceiver. The sensors considered in this review include acoustic, magnetoelastic, and electromagnetic transducers. They are presented through their relevant technological aspects and through they major advantages which include their integrability within embedded systems and/or systems requiring energy autonomy. Furthermore, the use of these resonant sensors is illustrated in a large variety of applications, ranging from environmental monitoring, structural health monitoring, food packaging monitoring, wearable or implanted sensors for the monitoring of physiological parameters in healthcare related applications, to IoT and future industry monitoring applications.**

***Index Terms*— Acoustic transducer, Microwave transduction, Remote sensing, Energy harvesting, Wireless LC resonating sensors, Straintronics transducers, Phononic crystal, Implanted sensor, Physical sensor, Biosensor, Gas sensor, Passive resonant device.**

I. Introduction

SCIENTIFIC and technical progress yielded to consider satisfactorily the detection and real-time monitoring of surrounding physical quantities or of chemical or biological substances in gaseous or liquid environments including biological fluids. Physical sensors (temperature, pressure, strain, acceleration, magnetic field…) are already used extensively in the manufacturing, and employed across a wide range of sectors, including automotive, consumer, etc. Predictive maintenance and early failure detection, vibration monitoring, industrial Internet of Things (IoT) and connected devices are examples of key applications. Commercial platforms also allow the detection, diagnosis, monitoring, or quantification of measurands of interest at concentrations down to a few particles per billion (ppb) and µg/L of chemical or biological species, at a cost from a few hundred to a few thousand dollars. The combination of low-cost sensor's design and power optimization is crucial for Industry 4.0. It will result in responsive and agile production processes with sensors integrated in the entire product lifecycle.

Considering applications related to gaseous fluids monitoring, commercial systems are based on various principles. Some sensors claim the identification of explosion risks such as pellistors and infrared detectors [1]. Among devices and detectors dedicated to the real time detection and monitoring of gases or volatile organic compounds (VOCs) at low concentrations, electrochemical sensors, Metal Oxide (MOx) sensors, Photo-Ionization Detector (PID) and mass spectroscopy are the most widespread [2]. With regard to the analysis of biological and liquid fluids in medical or environmental applications, usual techniques are spectrometry of atomic emission of plasma induced by laser [3], cyclic voltammetry [4], real-time Polymerase Chain Reaction (PCR) and high performance liquid chromatography (HPLC) [5], Enzyme-Linked ImmunoSorbent Assay (ELISA) [6], radioimmunoassay (RIA) [7] and immunofluorescence [8]. However, these systems are often costly and they require time and highly qualified staff due to the instrumentation techniques and associated signal analysis.

Despite remarkable technological advances, the development of sensors with high sensitivity, stability, scalability, reproducibility, taking into account the impact of interfering environmental factors, Low limit Of Detection (LOD), effective selectivity vis-à-vis biological or chemical species, energy autonomy, easy results exploitation, and a reasonable level of cost, remains an ultimate challenge [9]. It is also worth noting that some conventional transducers associated with nanostructured materials such as metal oxides and semiconductors operate at high temperatures or at low frequencies or with bulky and expensive characterization tools,

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therefore requiring specific instrumentation and substantial energy consumption. This hampers the development of on-board or communicating systems, thus their deployment in live environment and cost-effective marketing.

On the other hand, the human environment is rich with natural and artificial resonators, ranging from crystal lattice vibration, musical instruments to complex devices such as quartz clock, lasers, spectrometer systems. Usually, a resonance refers to be an increase of the response of a system to an external excitation at a particular frequency equal or close to its natural internal one. Many physical systems also exhibit the opposite phenomenon, when their response is reduced or suppressed if some resonance condition is satisfied; this is referred as antiresonance. The resonance in the form of standing waves or resulting from scattering waves underlies many familiar resonance phenomena in electronics, optics and acoustics. As a consequence, resonators can be designed in various ways based on acoustic, electromagnetic, optic and electronic wave's interferences and their coupling. For sensors, resonance can be energyless, it allows high accuracy and high signal to noise ratio measurements to be carried out, acting as a selective filter to reject the useless part of the signal. Resonating transducers based on a wide range of wave frequencies, such as radiofrequency [10], acoustic waves [11], and microwaves [12], have been reported. These technologies are intrinsically passive, generic, portable, and suitable for high frequency operation, thus possibly wirelessly readable. Their manufacture is inspired by semiconductor or additive technologies, therefore allowing mass production at attractive prices. Furthermore, the operating principles can be complementary. For example, acoustic platforms offer exceptional sensitivities to mechanical surface effects, namely viscoelasticity and mass density, while electromagnetic waves are especially sensitive to electrical variations including permittivity and conductivity. Their association with various structured nanomaterials operating at ambient temperatures, ranging from organic, inorganic semiconductors, mesoporous materials, carbonaceous and other 2D-like nanostructured ones, solid electrolytes to conductive or polymer materials, yielded small detection devices, with low energy consumption and high sensitivity. Room temperature operation is also a key asset for flammable operating environments.

In this context, this review proposes a focus on the most common and promising passive resonant sensors which have revolutionized real-time measurements. The first part deals with a detailed review on acoustic, magnetoelastic, microwave and radio-frequency transducers principles and remote sensing. Then, a plethora of applications is illustrated. Finally, a synthesis and development prospects are reported and discussed.

II. Resonant sensor principles & interrogation

A. *Surface and bulk wave acoustic platforms*

Electromechanical devices operate by providing a frequency shift which is impacted by the inertial mass of surrounding parameters and molecules undergoing the mechanical wave motion. Among the most sensitive transducers are those based on the acoustic vibrational modes of crystals, thin films and microcantilevers [13, 14]. The common high frequency ones are based on bulk acoustic waves (BAW), surface acoustic waves (SAW), or plate waves (e.g. APM for Acoustic Plate Mode) [15]. Such devices use both the direct and the reverse piezoelectric effect, with bilateral conversion between electrical energy and mechanical wave. The acoustic wave propagation velocity is the basic sensor output signal, which is influenced, among others, by changes in the mass mechanically linked to the device surface.

The oldest acoustic detection device is the quartz crystal microbalance (QCM) which is part of the BAW devices, with typical frequencies of a few MHz or tens of MHz. It has been widely used for the detection of target compounds and surrounding physical parameters such as temperature and pressure [16]. Shear horizontal acoustic plate modes (SH-APM) and Lamb waves propagating in piezoelectric thin film devices, typically in the frequency range of 2-200 MHz, are commonly studied [17, 18]. However, a good surface sensitivity and mode separation would require unrealistically thin plates. Recent developments in the BAW devices family include thin film bulk acoustic resonators (TFBAR or FBAR) which mainly consist of thin films of aluminum nitride (AlN), scandium doped AlN (Sc-AlN) or zinc oxide (ZnO). Such piezoelectric films are either solidly mounted on a supporting structure integrating a Bragg acoustic mirror (SMR) or on a membrane cavity. FBARs can operate in longitudinal or in thickness shear mode, the latter being preferred for liquid operation to minimize energy losses. The FBARs operating frequencies range from sub-GHz to tens of GHz [19, 20].

SAW devices operate at frequencies in the MHz to GHz range. The wave propagating at the surface of the piezoelectric material is generated and recovered by interdigital transducers (IDT) in delay line or resonator configuration. The spacing between the two IDTs in a delay line causes a delay between the input and output signals. In the two-port resonator configuration, the input and output IDTs are closer to each other and surrounded by reflective fingers. Single port resonators have a single IDT with reflective fingers on both sides (like a Bragg mirror). Quartz, lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$) are common piezoelectric materials in SAW sensors. Depending on the piezoelectric material and its crystal orientation, different types of waves are generated. The Rayleigh wave combines longitudinal and vertical transverse polarizations [21], it is commonly used in the telecommunication domain (SAW filter, frequency pilot), and is well adapted for measurement of physical quantities and in gaseous fluids. The Bleustein-Gulyaev wave is a shear horizontal SAW mode, also studied for sensor [22].

Whatever the bulk, plate or surface wave type, any vertical component in the polarization leads to significant signal attenuation (losses) in liquid media, due to radiating compressional waves in the liquid. Therefore, acoustic devices for liquid operation require horizontally polarized shear waves

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TABLE I
A SURFACE AND BULK WAVE ACOUSTIC PLATFORMS: KEY DESIGN PARAMETERS & CHARACTERISTICS

Wave form	Acoustic device: wave mode, key material and operating frequency (fr)	Sensitivity to mass load $Sm = \frac{\Delta f}{f_0\, \Delta m}$	Advantages	Technological limitations
BAW	**QCM (TSM: Thickness Shear mode)** AT cut Quartz Fr in the 5 to 10 MHz range Maximum limit reached: 50 MHz	20 – 100 cm²/g 20 cm²/g @10 MHz $\lvert Sm \rvert = \frac{2 \times f_0}{\rho \times v} = \frac{1}{\rho \times h} = \frac{A}{m}$ $\Delta f = \frac{2 \times f_0^2}{v} \times \frac{\Delta m}{A}$ Sensitivity ↑ → frequency ↑ → Substrate thickness ↓ (process limitation)	Immersion in liquid environment Quite easy to use Inexpensive and low cost Mature technology	Low detection resolution due to low operating frequency Thick substrate (> 20 µm) and large surface area (> 1 cm²) → non compatible with downscaling
	FBAR: Film bulk acoustic wave resonator Back side etch or Back trench Defined by the materials thickness and acoustic wave velocity Materials: thin films based on AlN or ZnO or PZT From Sub to tens GHz	1000 cm²/g Sm depends on the thin film thickness $\lvert Sm \rvert = \frac{2 \times f_0}{\rho \times v} = \frac{1}{\rho \times h} = \frac{A}{m}$ $\Delta f = \frac{2 \times f_0^2}{v} \times \frac{\Delta m}{A}$ Reducing the mass of the transducer to bring it close to loaded mass → improve the sensitivity	Small reference mass → Very high sensitivity Can Operate @ high frequency Ability to fabricate using complementary metal oxide semiconductor (CMOS) technology Significantly reduced size and volume The device can operate in longitudinal mode or in thickness shear mode.	Excessively fragile to handle. Excitation of shear wave requires piezoelectric thin films with specific properties: ZnO and AlN with tilted c-axis. Longitudinal acoustic modes are not compatible with immersion → quality factor reduced → impact the S/N ratio.
	FBAR : Front side etch or air bag		Simple fabrication process using sacrificial layer	Same as FBAR back side etch
	SMR : Solidly mounted resonator Bragg acoustic mirror		+ More robust structure + Choose of supporting substrate → free	+ More film deposition processes → time consuming and process complexity.
SAW	**SAW : Rayleigh** Evanescent wave ~ 100 MHz defined by the IDTs period and acoustic wave velocity	100 – 200 cm²/g $\mathrm{Sm} = \mathrm{C1} \times \frac{f_0}{A}$ $\Delta \mathrm{f} = \mathrm{C1} \times \frac{f_0^2}{A} \times \Delta m$ 8000 cm²/g @ ~10GHz	SAW devices technology compatible with frequency increase → improve sensitivity Compatible with microfluidic chips and with co-integration with other transduction principles	Ineffective in probing reactions in liquid media-→ strongly damped when the surface is in contact with liquid
	SAW : Shear SH Leaky Evanescent wave		+Immersion possible	Penetration depth very high → ratio of perturbed to unperturbed volume small
	SAW : Love Guided wave	150 – 1000 cm²/g	+ Highest sensitivity among SAW sensors due to the wave guiding effect Able to propagate in liquid environment	
FPW	**FPW : Film plate wave** S0 mode A0 mode SH0 mode	$\lvert Sm \rvert = C_2 \times J \times \frac{A}{m}$ C_2 depend on the mode dispersion behavior	Combine advantage of FBAR and SAW devices	Excessively fragile to handle. Radiation loss could occur in liquid in the case of S0 and A0 modes.

Δf: frequency shift to a variation on surface mass (Δm); A area of active surface, f_0 resonance frequency, v : phase velocity of the mode, ρ and h are the propagating piezo material density and thickness respectively. Sm mass load sensitivity, m resonator mass reference. C_1 and C_2 are constants that include the contribution of mode dispersion in the case of SAW and FPW devices. J = 1/2 for the mode n = 0 and J = 1 for higher plate modes (n > 0).

(HPSW). This includes Love waves, guided in a thin surface layer, and surface transverse waves (STW), confined by a network of metal bands. Such SAW-like devices can be used for liquid, gas and physical parameters detection applications [23]. SAW and BAW platforms are produced by standard lithography processes, which allow mass production.

In general, the acoustic wave resonance frequency can be affected by many factors, each of which presents a potential sensor response. Equation (1) illustrates the relative frequency variation as a function of variation of mass (m), electrical field (E), mechanical stress (σ), Temperature (T) and any other perturbation of the resonator environment.

$$\frac{\Delta f}{f_0} \cong \frac{1}{f_0}\left(\frac{\partial f}{\partial m}\Delta m + \frac{\partial f}{\partial E}\Delta E + \frac{\partial f}{\partial \sigma}\Delta \sigma + \frac{\partial f}{\partial T}\Delta T + \frac{\partial f}{\partial envi}\Delta envi\right) \quad (1)$$

The partial derivation of frequency to a given perturbation defines the sensitivity of acoustic wave devices. It depends generally on the dispersion curves behavior under perturbation of the investigated mode, on the ratio between perturbed and unperturbed waveguide or resonator volume and on the operation frequency. Mass effect is the most intuitive principle

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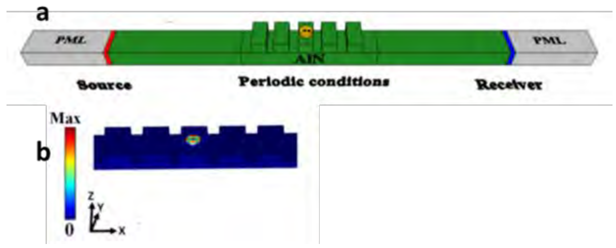

Fig.1. a) Waveguide representation with cavity resonator made of nanomaterials as a cap layer. b) Localized whispering gallery mode in the cap layer.

in various acoustic wave sensors. To improve the sensitivity of acoustic wave mass sensors one should first choose the appropriate mode based on the dispersion curves sensitivity, secondly, increase the operation frequency, and thirdly to reduce the resonator mass reference to bring it close to that of equivalent loaded mass. Table I provides an overview of some surface and bulk wave acoustic platforms compared in terms of their wave form and mode, design, materials, operating frequency, sensitivity, advantages and technological limitations.

In order to improve the performances of acoustic wave sensors in terms of sensitivity and LOD, several works report on the use of phononic crystal and metamaterials analog to photonic and plasmonic in optics. The ability to control the propagation of elastic waves with such composite materials has attracted a considerable attention during the last two decades from science and technology points of view. Based on the concept of bandgap and its properties, these artificial materials enable to implement advanced sensing and signal processing functions: wave-guiding, trapping, multiplexing, demultiplexing, etc. By combination of micro- and nanoscale resonators made of functional nanomaterials, and RF electroacoustic microwave, one can achieve advanced engineering of surface localized modes sensitivity and LOD. During the last decade, various designs for cavity resonators with high Q factor are reported in the literature showing all the promise for this new technology line [24, 25, 26, 27]. An example of metamaterials cavity design is shown in Fig. 1.

B. Acoustic sensors in wireless configurations

In addition of being small, simple and robust, SAW devices can be batteryless, possibly wirelessly interrogated [28] and packageless [29, 30], with multi-tagging (IDTAG) capability [31, 32]. SAW devices being widely used as standard components of RF communication, SAW sensors and their reader units can be inexpensive and several solutions are commercially available [33, 34, 35, 36]. For applications in harsh environments, SAW sensors can be operated wirelessly, being used in backscattering mode an controlled by the RF electronic reader located in a safe area. Two such configurations can be considered: resonators or reflective delay lines.

- Reflective delay line (R-DL) configuration: an IDT is connected to an antenna with reflectors on the surface wave propagation path (Fig. 2). The remote interrogation system sends microwave pulses to the sensor. The IDT converts the

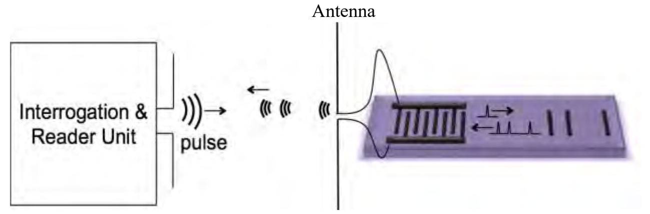

Fig. 2. Principle of a wireless SAW sensor in reflective delay line configuration.

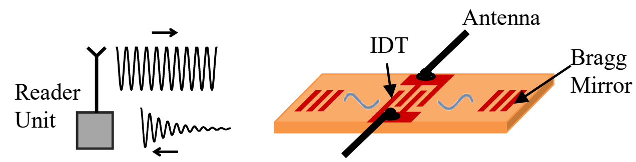

Fig. 3. Principle of a wireless SAW sensor in resonator configuration.

electromagnetic pulse from the antenna into an acoustic one, which travels along the SAW device and is partially reflected due to the difference in acoustic impedance of the reflectors (usually metallic lines) with the substrate. This backward wave is turned back into a radio echo by the IDT and the antenna, towards the remote processing system. A modification of the environmental parameters results in a variation of the time elapsing between the reception of each echo, and of the echoes magnitude (Fig. 2). For wireless R-DLs, it is critically important to use substrates with high electromechanical coupling coefficient k2, low propagation loss and low power flow angle, and well as electrodes with low viscoelastic losses. Design-wise, well defined peaks with similar amplitude are favored.

- Resonator configuration: an IDT is placed between two acoustic Bragg mirrors, to form a high quality factor resonant cavity (Fig. 3). The resonator can be excited wirelessly by the interrogation system at a frequency close to the resonant frequency of the cavity. When the excitation is switched off, the resonator keeps oscillating freely for a period of time at its eigenfrequency, which is dependent on the environmental parameters. The detection of these free oscillations will be easier with high Q resonators, since the higher the quality factor Q is, the higher the frequency resolution will be. Also very important is the figure of merit (FOM) equal to $Q*k^2$, since it determines the power re-radiation efficiency of the resonator, as well as the optimal matching [37]. Hence, the quality factor and the figure of merit are therefore essential parameters for the production of efficient wireless SAW resonators.

The Interrogation principle is based on radar technique and a variety of architectures such as time domain sampling (TDS), frequency domain sampling (FDS) or hybrid concepts for both R-SAW and R-DL sensors have been also investigated and reported by Lurz *et al.* [38].

C. Electromagnetic Radio Frequency (RF) platforms

Passive electromagnetic RF resonating sensors are based on an electromagnetic field operating in the hundreds of kHz up to the THz frequency range, to detect, evaluate or monitor changes in the matter under test (MUT). The electromagnetic field

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propagation is affected by the dielectric properties of the MUT. These properties are modelled by the complex permittivity ε^* as in (2):

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (2)$$

where $\varepsilon'$is related to the polarizability of the matter, and the imaginary part ε''represents the dielectric losses and is related to the conduction and displacement currents induced within the matter. As a result, changes in the dielectric properties of the MUT induced by its structural, chemical, or physical changes, strongly affect the resonance of the sensor interacting with it. The sensitivity S of the sensor to dielectric changes can be generally defined as in (3):

$$S = \frac{\Delta f}{f_0 \, |\Delta\varepsilon *|} \quad (3)$$

where $|\Delta\varepsilon *|$ denotes the dielectric changes and Δf denotes the induced resonance frequency shift, comparatively to the unloaded sensor or to the sensor loaded by a reference matter. The choice of the operating frequency is related to the desired scale of investigation of the MUT [39].

In the lower range of the RF spectrum (hundreds of kHz to tens of GHz), passive inductor-capacitor (LC) resonant sensors are widely used since the 1960's as they provide sensitive, versatile, easy to design and wireless sensing solutions [40]. The LC circuit acts as a resonant energy tank, characterized by its resonance frequency f and quality factor Q, as in (4):

$$f = \frac{1}{2\pi\sqrt{LC}} \text{ and } Q = \frac{1}{R}\sqrt{\frac{L}{C}} \quad (4)$$

where R denotes the losses in the resonator. The modifications of the dielectric properties of the MUT, induced by either structural, chemical or physical changes, will modify the R, L, and/or C parameters, and hence the resonance of the sensor. These changes can be readout through the impedance of a distant monitoring coil, inductively coupled to the LC sensor (Fig. 4.a.). This feature enables wireless implementation, and makes passive LC sensors especially good candidates for low invasive monitoring applications in harsh, sealed or low accessibility environments, which strongly benefits from recent developments in microfabrication technology which allows flexibility, miniaturization, functionalization and minimal invasive sensing solutions to be reached [41, 42].

On the other hand, microwave transducers are usually implemented in the upper range of the RF bandwidth, i.e. from hundreds of MHz to THz. The evaluation by direct measurement of the dielectric properties of a sample used as a waveguide or resonator charge, as illustrated in Fig. 4, b, is dedicated to the estimation of the permittivity of a fluid or of a solid [43, 44, 45, 46]. The association of a microfluidic chip has further contributed to using this type of measurement for applications requiring detections in liquid media [47, 48]. Structures based on metamaterials (Fig. 4, b) have improved the sensitivity of this type of sensors, notably thanks to the concentration of the electromagnetic field [49].

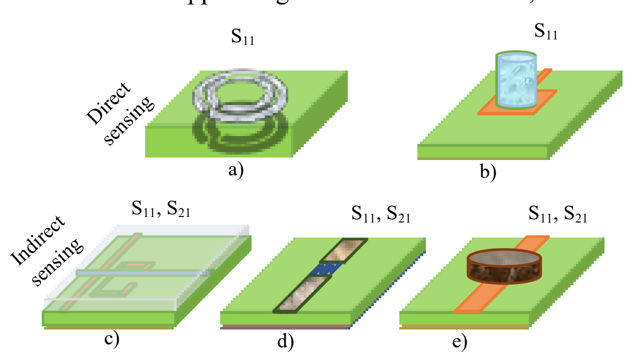

Fig. 4. Principle of direct and indirect microwave sensor. Scattering parameters are obtained by vector network analyzer. a) LC resonator, b) Antenna in contact to the sample, c) Metamaterial sensor associated to a microfluidic set-up. d) Conductive lines of the sensor and the sensitive material. e) Microwave circuit is covered (locally) by the sensitive material.

At the same time, a new generation of microwave sensors has emerged over the past two decades. It uses indirect detection (Fig. 4, c, d and e) based on monitoring the evolution of the dielectric and conductive properties of an additional chemical material immobilizing or reacting with the target chemical or biological species. Their geometries generally based on miscrostrip and coplanar lines have facilitated low cost manufacturing [50].

This type of microwave transducer can meet three major challenges in the field of sensor research. First of all, they can be designed with a large variety of materials. Secondly, they can operate at room temperature. Third, the sensor response is directly related to the excitation frequencies, allowing a better understanding of the interaction of target molecules and sensitive materials in the microwave range. Indeed, the dielectric properties are influenced by the surface interactions between the sensitive material and its environment, such as adsorption (physisorption, chemisorption), the covalent bond and Van der Waals or the dipole-dipole interactions. The choice of the sensitive material is driven by the end application [51]. It can be deposited locally [52, 53, 54] or covering the entire surface of the resonant circuit [55].

Table II provides an overview of some electromagnetic RF transducers compared in terms of their application environment, design, materials, operating frequency, sensitivity, and target quantity measurement. Examples of applications are also detailed in section III.D.

D. Sensing, energy harvesting and power transmission

Active materials such as piezoelectric ceramics and magnetoelectric composites used in passive resonant sensors enable to consider extended functionalities of power transfer and energy harvesting [56]. The extracted electrical energy can then be used to power small electronics circuitry in order to get smarter passive sensors with enhanced features and embedded intelligence. In that perspective, a magnetostrictive transducer was designed for simultaneous vibration sensing and energy harvesting [72].

This sensor exhibited a sensitivity as large as 55 V.s/m thanks to the small electronic interface powered by the device itself. In terms of energy harvesting, the magnetostrictive transducer provided output powers in the range of 10-50 µW. The authors suggested that such vibration sensor could power its own wireless communication node. With similar approach and objectives, a self-powered sensor based on triboelectric effect was developed to monitor the vibration frequency of drill strings [73].

TABLE II
ELECTROMAGNETIC RF SENSORS: CHARACTERISTICS AND APPLICATIONS

Electromagnetic-wave propagation	Design	Key Material	Measured quantity	Measurement principle	Operating frequency and Sensitivity	Technological limitations	Notes	Refs.
Near field volumic propagation	Planar monolithic	Nano-silver paste tracks printed on paper	Relative Humidity in the 11 to 97% RH range	$f = \frac{1}{2\pi\sqrt{LC}}$ With C humidity sensitive	@182 MHz 140 kHz/RH	Low Q	Wireless read , low cost, , Reader position-independent	[57]
	Multilayer monolithic	Tungsten tracks embedded in alumina ceramic	Temperature in the 0 – 1000°C range	$f = \frac{1}{2\pi\sqrt{LC}}$ With C temperature sensitive	@27.6 MHz 2 kHz/°C	Complex fabrication process: high temperature cofired ceramics	Wireless read	[58]
	Planar flexible monolithic	Gold tracks micro patterned on PDMS	Normal stress in the 100 kPa range	$f = \frac{1}{2\pi\sqrt{LC}}$ With C humidity sensitive	@160 MHz 2.37 MHz/ kPa in the 0-10 kPa range	Temperature sensitive, Sensitivity decreases with high pressure	Wireless read, Response time 67 ms	[59]
	Planar flexible monolithic	Graphene, gold tracks, soluble silk film substrate	Bacteria concentration in the 108 colony-forming units (CFU)/ml range	$f = \frac{1}{2\pi\sqrt{LC}}$ With C humidity sensitive	20 %/10^6 CFU.ml-1	Sensitive to analyte coverage and air bubbles	Wireless read, Reader position independent, In-vitro implementation	[60]
	Multilayer Split ring	Glucose sensitive PBA hydrogel, aluminum electrodes	Concentration of glucose (mg/dl)	$f = \frac{1}{2\pi\sqrt{LC}}$ With C glucose sensitive	@550 MHz 304 kHz / (mg/dL)	1hour response time, long term sensitivity beyond 45 days	Wireless read. Ex-vivo feasibility demonstrated with subcutaneous implementation	[61]
	Planar monolithic and flexible	Copper tracks on polyimide substrates +PDMS deformable dielectric layers	Moisture (20-90 %RH range) & Pressure (0-100 mmHg range)	$f = \frac{1}{2\pi\sqrt{LC}}$ With C pressure / moisture sensitive	@80 MHz and 550 MHz -61 kHz/%RH -388.6 kHz/mmHg	Expected lower sensitivity in in-vivo implementation	Wireless readout, feasibility demonstrated in-vitro	[62]
	Multilayer flexible Monolithic	CuFlon	Complex permittivity changes related to burn depth (0 to 9 mm)	ΔL/L related permittivity changes and ΔR/R to conductivity changes	@300 MHz ΔL/L= 4.5%/mm ΔR/R=3.3%/mm	Reader-resonator distant dependent.	Validated on ex-vivo samples	[63]
	Cylindrical monolithic	CuFlon	Complex permittivity changes	ΔL/L related permittivity changes and ΔR/R to conductivity changes	@98 MHz ΔR/R =30% and ΔR/R =40%, for 300 min incubation time @60°C	Resonator surrounding the sample, temperature dependent	Non contact, longtime monitoring assessment of complex permittivity absolute values	[64]
Volumic propagation	On port coaxial structure	SnO_2, $SrTIO_3$, TiO_2, $ZnSO_4$ and ZrO_2	Saturation vapour pressure	S11 real and imaginary parts variation	@2 GHz Δ(Im(S11)/Im(S11) = 0.3%/mBar water 0.23%/mBar Toluene (with $SrTIO_3$)	Conception of the isolator (compression of metal oxide powder)	Difference of response between toluene, water and ethanol	[65]
	Dielectric resonator on pcb circuit	SnO_2	100 ppm Ethylene	-	@10 GHz S21	Adhesion if sensitive material on the dielectric resonator	Adaptability of wireless communication	[66]
Surface propagation	PCB Circuit (microstrip)	TiO_2 & Fe_2O_3 superstrate	100-500 ppm NH3 in Ar	Shift of S11 parameter	@2.2GHz 0.034 dB/100 ppm 10^{-4}/100 ppm	Homogeneity of sensitive layer	Influence of the crystal morphology	[67, 68] [69]
		Surperstrate of CuO	0-200 ppm acetone	Shift of phase (S11)	@2.4 Ghz 1deg/100ppm	Drift of baseline		[70]
	Inkjet-printed flexible PCB	Carbon nanocomposite	0-1300 ppm ethanol	Shift Resonance frequency	@2.5 GHz 0.646 kHz/ppm	Influence of flexibility of the response	Differential measure	[53, 71]

Acoustic power transmission in air was studied using a capacitive parametric ultrasonic transducer (CPUT) [74]. A 40 µW electrical power was generated by the CPUT excited at 50 kHz. It enabled to wirelessly power its interface circuit used for both reducing the parametric threshold and tuning the directivity of the CPUT, thus providing improved performance to this passive resonant acoustic sensor.

III. Applications

A. Acoustic waves based platforms for chemical and bio sensing and monitoring

The association of chemical nanostructured materials and acoustic platforms undergoes an ever-growing importance in VOCs and harmful gases monitoring, especially for issues related to our ecosystem and environmental health, also to some chronic diseases. Most significantly, it was reported real time detection at room temperature of a few ppm of hydrogen (H_2) gas by using metals and oxides such as Pd [75], Pt/ZnO [76], In_2O_3 [77], etc. In addition, polymers such as PECH, PEI, PIB, PMPS, were used for the detection of traces of DCM, EtOAc, DMMP, n-octane and toluene vapors [78, 79, 80, 81]. We have also witnessed a remarkable breakthrough in recent studies reporting the interest of carbon materials such as graphene, CNTs and their derivatives. This relies on their excellent mechanical properties especially for the design of acoustic platforms [82, 83, 84], their integrability in standard or additive micro-technology processes [85], and the possible functionalization to provide selectivity in addition to their outstanding sensitivity at ambient conditions [86]. Among these works, GO-based acoustic transducers led to sensitivities of 4.7 Hz/ppb and 102 Hz/ppm to NH_3 and NO_2, respectively [87]. The corresponding experimental detection limit (LOD) was estimated to be 30 ppb for NH_3 gas and 25 ppb for NO_2. Another study confirmed the sensitivity and specificity of GO flakes to ammonia gas in comparison to H_2, H_2S, CO and NO_2 gases [88]. Sayago *et al.* [89] reported high sensitivities of 3087 Hz/ppm to DMMP and 760 Hz/ppm to DPGME with the same type of sensitive material. A shift of 25 kHz to 0.5 % of H_2 concentration was reported, with good repeatability and stability, by using a SAW platform associated with Pd-Gr nanocomposite [90]. Similarly, SWCNTs were investigated with SAW platform for the detection of ethyl acetate and toluene vapors with sensitivities of 5.45 kHz/ppm and 7.47 kHz/ppm, respectively [91], and a SWCNTs - Cu nanoparticles composite based SAW platform exhibited a sensitivity of 2.6 kHz/ppm to H_2 gas [92].

For applications related to fluid samples analysis, the sensor sensitivity is strongly influenced by the receptor, or active sensitive layer, by the process of its immobilization, as well as by the wave mode and the detection approach, while specificity is determined by an available combination of biological or chemical recognition [93]. A common strategy relies on biological receptors immobilized on the acoustic platform surface, consisting of antibodies [94], nucleic acids [95], enzymes [96], cells [97] and microorganisms [98]. However, a large part of such biosensors suffers from a poor stability and reliability due to a short lifetime. Moreover, mass production with standard methods is still a major challenge, mainly related to immobilizing living matrices on the surface.

Another approach is based on the association of chemical recognition films aiming at improving the analytical performance, reliability and mass production. The signal amplification process usually also involves a nanomaterial-based inter-layer or matrix to link the bio-recognition element to the acoustic device surface. For example, among studies exploring this approach for cancer biomarkers detection, different acoustic platforms have been successfully associated with gold (Au) nanoparticles [99], PZT [100], Parylene C [101] and Molecularly Imprinted Polymer (MIP) [11, 102].

Recently, research findings have also highlighted the interest of materials such as recyclable polyethylene naphthalate associated with a SAW sensor for the detection of *E. coli* bacteria [103], or the association of a Love wave platform to the 2D composite rGO-MoS_2 flakes synthetized with Au nanoparticles and the polyamic acid diethyl ethanolamine salt precursor for the carcinoembryonic antigen detection [104].

B. Acoustic waves based platforms for physical parameters monitoring in harsh environments

The use of SAW devices as passive and wireless sensors makes sensing possible in rotating parts [105] and allows them to operate in extreme conditions such as those with high levels of radiation, temperatures up to 1000°C or electromagnetic interference, where no other wireless sensor can operate [106]. Obviously, this is possible if the constituting materials can withstand these harsh conditions [107]. Combined with flexible substrates [108], SAW sensors also find applications in the biomedical and welfare industry, such as continuous monitoring of the human body's parameters, either on skin [109] or in implants [110], which are another type of "harsh" environments due to RF and acoustic absorption.

For high temperature applications, the choice of the constitutive materials of the SAW sensor is critical. For example, conventional piezoelectric material such as quartz, $LiNbO_3$, and $LiTaO_3$ are unusable at high temperature (above 400°C). Indeed, Quartz undergoes a phase transition at 573 °C and exhibits an increasing structural disorder from 400 °C, which decreases considerably its piezoelectricity and thus the quality factor of SAW devices. The relatively low Curie temperature of Lithium Tantalate (600 °C) limits its use as substrate in harsh conditions. The Lithium Niobate ($LiNbO_3$ - LN) Curie temperature around 1200 ° C is advantageous, but its electrical conductivity strongly increases with temperature, reaching the value of 105 Ω.cm at 600 °C. This induces significant electrical losses (leakage currents), preventing any use in a wireless configuration. However, thanks to its high electromechanical coupling coefficient (K^2), a few studies still consider LN at moderate temperature below 400 °C and especially in R-DL configuration. They were all based on It should be noted, however, that studies conducted on the use of LN for SAW applications at high temperatures are ultimately relatively few. They were all made with readily available LN crystals of congruent composition (cLN). Hornsteiner *et al.*

[111] showed that the insertion loss of SAW delay lines based on cLN and platinum IDTs, operating at 100 MHz, remains very stable up to 500 °C, then increases rapidly, which is probably linked to the increase in electrical conductivity described above. Hauser *et al.* [112] confirmed in 2003 a lifetime of at least 10 days at 400 °C of SAW devices based on cLN. Beyond that, again, the lifetime decreases quickly, down to a few hours only at 450 °C. The authors explain that this phenomenon is not related to a degradation of the crystal, but to a damage of the IDTs (nature not specified) which they attribute, in a hypothetical way, to the formation of sparks related to the pyroelectric properties of the crystal. Fachberger *et al.* developed in 2006 wireless R-DL operating at 2.45 GHz, with cLN crystals [113]. Their lifetime is estimated at least 10 days at 350 °C, but only a few hours at 400 °C, due to the degradation of the aluminum IDTs. Finally, it was shown very recently that stoichiometric $LiNbO_3$ (sLN) substrates allowed slightly upper temperatures [114], and that SAW devices based on cLN could be operated up to 600°C for a few hours [32] and even up to 4 days [115]. Ultimately, very few piezoelectric media can be considered for applications above 400 °C. Currently, the Langasite ($La_3Ga_5SiO_{14}$ - LGS), which does not exhibit a phase transition up to its melting point at 1470 °C, is considered as one of the best-suited choice for such harsh environments. It was demonstrated that LGS-based SAW devices can be operated for at least 5 months at 800 °C [116] and over 150 hours at 1000 °C [117].

Another alternative consists in using layered structure with AlN as piezoelectric thin layer and sapphire as substrate. Such AlN/Sapphire SAW delay line using Iridium as electrodes could be operated for more than 40 hours up to 1140 °C [118], limited by electrodes instability. Recently resonators with high quality factor up to 8000 were achieved on an AlN/Sapphire structure [119]. These results are very promising for the achievement of wireless SAW sensors suited for high temperature environments.

At the same time, the reversible coupling between strain and other physical quantities is used to develop next-generation of signal processing functions including devices for information and sensors with the respect of energy-saving paradigm.

We will focus in this section on the straintronics based on magnetoelastic and piezoelectric materials, as the most promising coupling effect for designing highly sensitive and low LOD magnetic field sensor. Piezo-magneto-elastic heterostructures are composite structures generally consisting of a multilayer assembly of several materials, including a piezoelectric material and a magnetostrictive one. Exciting progress has been made over last two decades on magnetoelectric sensors, as highly sensitive magnetometers based on magnetic control of electrical polarization in magnetic/piezoelectric composite architecture [120, 121]. Such structures are now widely used in the development of current and magnetic field sensors [122, 123]. Two measurement principles are used. The first one is called direct magneto-electric effect, the presence of AC magnetic field induces oscillations of magnetization and through the magnetoelastic coupling a stress is induced in the piezoelectric material resulting in voltage across the piezoelectric layer. The magnetoelectric coefficient αME exhibits a maximum value when the AC magnetic signal matches the electromechanical resonance frequency of the structure. A high αME of 40 V/cm.Oe using AlN/(FeCo-TbCo)n composite structure is reported for the first time in 2007 [120]. This result was confirmed and improved by 20 orders of magnitude using the structure FeCoSiB/AlN and a detection limit of 400 fT/sqrt (Hz) was reported [121]. The design is very promising, however the operation in the resonance condition limits the ability to sense both DC and AC magnetic fields with the same LOD. Exploiting the direct magneto-electric effect in the case of a low-frequency magnetic field requires a broad structure, incompatible with integration and the technological processes used. The second principle is called ΔE effect, it is based on the frequency modulation of a resonant electromechanical structure. The ΔE effect enables to overcome these constraints [122], however the reported LOD of 1 nT/sqrt (Hz) remains very small in comparison to the previous one. During the last decade, there has been a renewed interest in the topic of sensors based on the combination of magnetoelastic thin films and surface acoustic wave devices. Two ways are investigated. First, increasing the ratio of magnetoelastic thin film to wavelength using confined acoustic waves results in ΔE effect improvement. The second way concerns investigation of acoustic wave driven Ferro Magnetic Resonance (FMR) that occurs when SAW operation frequency matches the FMR. The proof of concept of wireless magnetic SAW sensors based on ΔE effect has been reported in [123, 124] and full piezomagnetic model with experimental validation enabling to engineer the sensitivity of SAW magnetic fields sensor designs for both Rayleigh and Shear surface waves is reported in [125]. More recently, various studies were conducted to tackle the sensitivity improvement by using functionalized Love waveguide [126, 127] or thin film bulk acoustic wave [128]. Another work proposes to use directly the magnetoelastic material as Love waveguiding layer on ST-Quartz-cut, this enables to achieve the intrinsic limit sensitivity of the magnetoelastic thin film [129].

C. Electromagnetic RF platforms for complex matter monitoring and evaluation

Thanks to their intrinsic versatility, their possible planar geometry and to their possible miniaturization and association to advanced materials (flexible, functionalized, …) by means of microfabrication, passive LC sensors are particularly well suited to develop relevant wearable / implantable sensing solutions for plenty of applications as presented in Table II.

For example, Xie *et al.* [57] proposed a humidity sensor constituted of a silver nanowire based planar spiral LC circuit printed on paper for low cost food packaging assessment. The humidity sensing principle lies in the monitoring of the resonance changes induced by the humidity dependent capacitance of the LC circuit. Li *et al* [58] proposed a LC design based on a planar fixed coil and a parallel plate capacitor, embedded in a high temperature co-fired ceramic device, for high temperature wireless monitoring. Here, the sensing principle relies on the variations of the capacitor C with the temperature dependent dielectric constant of the ceramic substrate. Besides, LC designs on flexible substrate enable mechanical quantities to be monitored, as well as wearable sensors to be developed: Kou *et al*. elaborated a pressure/strain sensor by means of a graphene planar coil associated to a parallel plate capacitor, micro-patterned on compressible polydimethylsiloxane (PDMS) polymer [59]. The sensing principle lies in the change of the capacitance with the deformation of the stressed PDMS substrate. Flexible LC designs associated to advanced functionalized material allows wireless bio-sensors to be considered. For example, Mannoor *et al.* [60] developed a wearable pathogenic bacteria detector based on functionalized graphene electrodes allowing the specific binding of pathogenic bacteria, and integrated in a flexible LC circuit bio-transferred onto the surface of tooth enamel.

Furthermore, recent works have focused on implantable glucose monitoring by means of LC sensors [61, 130]. For example, Dautta *et al*. [61] recently proposed a millimetric double split ring resonator operating in the hundreds of MHz, dedicated to implantable settings for continuous glucose monitoring. The interlayer of the resonator is a phenylboronic acid hydrogel that swells and deflates as molecules of glucose bind and unbind to it. The observed resonator frequency shift is about 50 MHz per 150 mg/dL of glucose, with a detection limit of 10 mg/dL and a 1-hour step response (See Table II).

Other works focused on disposable medical dressings equipped with passive LC sensors for the non-invasive monitoring of dermal wound healing: Deng *et al.* [62] developed a centimetric flexible dual resonator integrating i) an interdigital capacitor for moisture sensing, and ii) capacitive plates for pressure sensing. The sensor operated in the tens and hundreds of MHz features sensitivities of about - 60 kHz/%RH in a 20%-90% RH range, and of about 400 kHz/mmHg in the 0-100 mmHg range; also, Dinh *et al*. [63] developed a centimetric flexible 300 MHz circular transmission line-based resonator, used to wirelessly sense tissue bio-impedance changes due to burn injuries. The sensor enables to assess the complex permittivity relative changes within the tissue (up to 60%) which fairly correlate with observed wound depth (up to 7 mm) and burning temperature (75 °C to 225 °C) and duration (up to 240 s) on ex-vivo pork meat samples.

More generally, LC resonators are well suited for the non-contact monitoring of physicochemical changes within organic matter. Using high-Q wireless transmission line-based resonators inspired by MRI setups [131] which operate as lumped RF LC tanks, Dinh *et al*. have distantly monitored the jellification of acidified milk solutions during yogurt formation [132], egg jellification during heating [64], through the sensing of the complex permittivity changes due to protein network restructuring within the organic matter. This approach opens the way to the development of minimally invasive / wearable devices for the monitoring of physio pathological state of tissues (ageing, dehydration, tumors). The limitations of such sensors lie mainly in the simultaneous sensitivity to multiple parameters (lack of specificity), the indirect measurement of physical or chemical quantities, and from the possibly distance-dependent wireless reading of the LC resonance. In this context, trend is towards the development of LC resonator arrays and multifrequency resonators [133] as well as multimodal implementation by means of passive electromagnetic-ultrasonic transducers [134] for enhanced characterization of organic matter.

Moreover, microwave transducers have shown their potential for the monitoring of vapors and toxic gases. For example, the association of metal oxides such as SnO_2, $SrTIO_3$, TiO_2, $ZnSO_4$ and ZrO_2 as sensitive material has been evaluated by Jouhannaud et al. [65]. These materials are used as dielectric insulator of the one-port coaxial structure (1-3 GHz) for ethanol, toluene and water vapors detection. In the following, dielectric resonators based on SnO_2 [66] and TiO_2 [135] sensitive materials, operating with whispering-gallery modes at 60 and 30 GHz frequencies respectively, were reported and the proof of concept of humidity detection was validated. In the case of ammonia detection, TiO_2 is used as supersubstrate for interdigital microstrip circuit (2 ports) [67]. Ammonia molecules (100-500 ppm) were adsorbed on sensitive material which coordinates NH_3 and NH_4^+ (surface Lewis acidity) [68]. A reversible variation of the response magnitude, image of the ammonia concentration, is observed, the shift is close to - 0.17 dB for S_{11} and + 0.1 dB for S_{21} (~ 2.2 GHz) at 500 ppm of ammonia (Fig. 5).

Among others, the crystal morphology is a key parameter of microwave sensing, as demonstrated by Bailly *et al.* [69] with hematite Fe_2O_3. Three typical particle shapes of hematite are used: spindles as one-dimensional structures, rhombohedra as high-index faceted crystals, and pseudocubes. Gas sensing experiments revealed that each morphology presents a different behavior upon ammonia injection. The response variation is less than 1dB. Detection of acetone vapor (0–200 ppm) was also demonstrated by Rydosz *et al.* [70]. Using a five port reflectometer, this study dealt with influence of sensitive material of CuO thicknesses (50 – 500 nm) on the sensor response; operating at 2.4 GHz.

Polymers and carbon nanocomposites and using of additive technologies were also reported this last decade. Krudpun *et al.* [54] used a Poly (styrene-co-maleic acid) partial isobutyl/methyl mixed ester (PSE), as super substrate of a coplanar interdigital resonator. The sensor response was evaluated in the range of 50 to 1000 ppm of ammonia with static

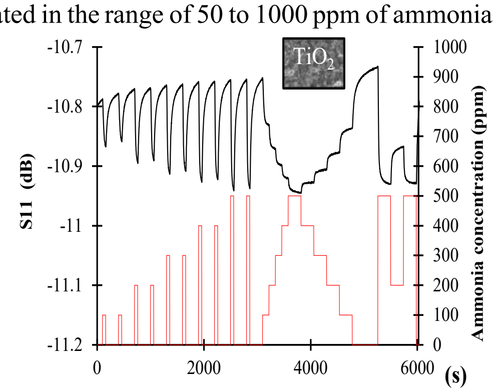

Fig. 5. Real-time quantitative and reversible response of an interdigital microwave sensor with TiO_2 (2.2-2.4 GHz) to ammonia vapors in argon as vector flow.

measurement set-up.

Chopra *et al.* [136] reported the first indirect microwave gas sensor (2002) associated with carb on nanotube layer (single and multiwall) deposited on a patch antenna structure. In static regime, ammonia was detected and leads to a 4 MHz downshift at 3.8 GHz. Moreover, Lee *et al.* [137] presented a sensitive antenna-based CNT sensor on paper. The whole flexible structure was inkjet-printed. In this study, the sensitivity to 100 ppm of ammonia was proved by a frequency shift of 50 MHz. In the same approach, Bahoumina *et al.* [53, 71] proposed an inkjet-printed flexible capacitive microwave sensor for VOCs detection in static and dynamic regimes. The sensor geometry allows a differential measurement in order to eliminate the influence of the physical interferent parameters (temperature, pressure) in gas quantification. In this study the sensitive material is a composite based on poly (3,4-ethylenedioxythiophene) polystyrene sulfonate and multi walled carbon nanotubes (PEDOT : PSS-MWCNTs). The sensitivity was estimated to –2.482 kHz/ppm [71] and 0.646 kHz/ppm [53] to ethanol vapor in the range from 0 to 1300 ppm, with sensors based on such capacitive resonator-based bandpass filter and stub-based microwave resonator, respectively.

Through different research works, by using microstrip and coplanar technologies combined with a great variety of sensitive materials, the versatility of microwave platforms designs is infinite. This technology also paves the way to explore hyper frequencies range for additional data based on the reaction between target molecules and sensitive materials electrical properties.

Furthermore, in microwave transduction, direct sensing method detection in liquid fluid is more developed than indirect technique. In direct sensing measurement, using a metamaterial structure associated with a microfluidic or a waveguide cavity-based sensor is more common [138]. The liquid sample induces a weak perturbation of the resonant circuit. Velez *et al.* obtained a quantitative relationship between the insertion loss (metamaterial circuit + microfluidic set-up) and electrolyte in water (NaCl; g/L). Genarellil *et al.* used a resonant cavity to evaluate NaCl concentration without microfluidic set-up. The interest of this approach is to obtain a direct estimation of the dielectric properties of the complete sample without dissociating the medium and the pollutant [139]. Very recently, Rossignol *et al.* [140] demonstrated an accurate quantification of chemical species at trace levels in a complex liquid with a microwave sensor. Based on microstrip technology, the shape of the microwave sensor is a multi-resonant circuit [1 - 8 GHz]. The molecularly imprinted silica (MIS) is specifically synthesized to detect the molecule of interest. The coupling between the circuit and the MIS allowed the specific detection of a pesticide like iprodione in hydroalcoholic liquid (10 - 100 ng/L) [140, 141].

IV. Future Challenges and Opportunities

Through this state of the art, it was reported the relevance of acoustic and electromagnetic passive resonators in various applications requiring tools for detection, monitoring or measurement in real time with reduced cost, adapted to unqualified users and in different environments. We noticed that the development of this type of sensors requires hybrid interdisciplinary efforts to overcome the technological, energy, environmental and health challenges. Despite the recent progress, the need for new platforms with high multiplexing and multimodality capacities for intelligent multiphysic and multichemical detection remains topical for many societal challenges. Two directions are possible to tackle the limits of current technologies: the first one implies innovation in the field of devices by combining smart efficient nanostructured materials from a technological point of view of integration; the second way is, on the one hand, to be ingenious in developing new intelligent systems by resorting to the association of complementary transducers and signal processing techniques ensuring relevant functions and on the other hand, to use techniques of artificial intelligence (AI) which are currently experiencing considerable progress.

The electronic nose “e-nose” and electronic tongue “e-tongue” for example are matrices including such criteria and are considered as one of the key solutions allowing to bring innovative solutions in the field of measurement, in particular for physical or chemical or biological quantities [50]. Such matrices are electronic systems imitating the biological olfactory and gustatory functions to identify odors or tastes [142]. Indeed, when physical quantities vary or the volatile chemical molecules and the droplets cross the network of sensors made up of transducers with multiple functionalization, the selective response of the sensor is recorded in the form of a “fingerprint” of the data. Multivariate data analysis and machine learning are emerging areas that offer performance and cost advantages for extracting valuable information from raw data sets. These techniques can perform exploratory and predictive analysis, which can help uncover hidden trends in the data used as descriptive variables for the target quantities to be measured [148].

Beside identifying the need for a platform integrating multimodal transducers and associating AI, the energy and wireless communication challenges are essential in IoT, monitoring of medical implants and patches, measurements in difficult access areas, security, etc. For this purpose, acoustic and electromagnetic transducers offer the advantage of being possibly passive and compatible with wireless readout, in particular thanks to their frequency response. Furthermore, these technologies can be operated at room temperature and they are compatible with mass and inexpensive manufacturing techniques. All these advantages pave the way for the proliferation of detection and control sites with the creation and multiplication of wireless communicating sensor networks and for portable powerful tools for analyte analysis.

V. Conclusions

Through this review, we have defined the requirements in terms of sensors needed to tackle the various societal challenges ranging from the environment to health issues, including security and the future industry and cities.

Thereafter, we presented an analysis of the elastic wave transducers developed to date with a comparison showing the important parameters for the design of acoustic devices adequate to the requirements of the targeted applications. The materials as well as the remote-sensing techniques used for monitoring purposes are described in the article. Likewise, the different categories of RF electromagnetic transducers have been discussed.

In addition, a review of some of the important research work carried out targeting various applications of these resonant acoustic and radio-frequency sensors, for analyte detections in gaseous and liquid fluids as well as for monitoring physical quantities, has been described. On the positive side, the innovation in designs, the availability of materials and the advancement in technology allowed for very sensitive resonators as reported in literature and illustrated in the tables included and the related discussions in terms of applications. However, there are still limitations to make these sensors marketable. Most of all, "selectivity" remains a major issue for current research in the field of chemical and biological sensors.

The section discussing future challenges and emerging potential solutions reports some directions that might spread to the needs desired.

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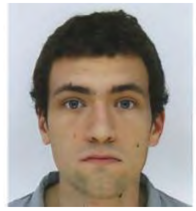

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