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Microwave-Enabled Wearables: Underpinning Technologies, Integration Platforms, and Next-Generation Roadmap

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ABSTRACT This paper presents a holistic and authoritative review of the role of microwave technologies in enabling a new generation of wearable devices. A human-centric Internet of Things (IoT) covering remote healthcare, distributed sensing, and consumer electronics, calls for high-performance wearable devices integrated into clothing, which require interdisciplinary research efforts to emerge. Microwaves, the "interconnect" of wireless networks, can enable, rather than solely connect, the next generation of autonomous, sustainable, and wearable-friendly electronics. First, enabling technologies including wireless power transmission and RF energy harvesting, backscattering and passive communication, RFID, and electromagnetic sensing are reviewed. We then discuss the key integration platforms, covering smart fabrics and electronic textiles, additive manufacturing, printed electronics, natively-flexible and organic RF semiconductors, and fully-integrated CMOS systems, where opportunities for hybrid integration are highlighted. The emerging research trends, from mmWave 6G, RF sensing and imaging, to healthcare applications including neural implants, drug delivery, and safety upon exposure to microwaves are re-visited and discussed, presenting a future roadmap for interdisciplinary research towards sustainable and reliable next-generation wearables.

INDEX TERMS Additive Manufacturing, Antennas, Backscattering, Energy Harvesting, E-Textiles, Flexible semiconductors, Harmonic Transponders, Rectennas, RFID, RF Sensing, Microwave Power Transmission, MTT 70th Anniversary Special Issue, Printed Electronics, Sustainable Electronics, Wearable Electronics.

I. Introduction

Bringing connectivity and intelligence closer to the user enables next-generation Internet of Things (IoT) to reach new remits in user-centric applications [1]. Wearables, the closest non-invasive interface to the user, enable IoT devices to provide near-real-time sensing, as well as enable a new level of integration of electronics in real-world use-cases.

Unobtrusive, pervasive, and sustainable wearable devices, however, possess a range of unique challenges, which require novel enabling technologies. Radio Frequency (RF) front-ends, typically the -wireless- "interconnect" of the IoT/IoE, can play a bigger role than simply transferring data. Decades of microwave engineering research on technologies originally unrelated to wearables, such as microwave Wireless Power Transmission (WPT), Radio Detection And Ranging (radar), as well as passive and low-power communication [2] can add new functionalities to wearables.

In this review, we illustrate how microwave technologies can *enable, as opposed to solely connect*, the next generation of wearables. The vision of microwave-enabled wearables (Fig. 1) is first introduced, in light of previous reviews addressing wearables research (Table 1). We then review the enabling technologies and integration platforms, surveying the state-of-the-art and identifying future cross-theme research challenges. Finally, the emerging trends and applications in wearable technologies are summarized in a roadmap, highlighting the route to a new generation of ubiquitous and sustainable wearable systems.

II. Microwave-Enabled Wearables

A. Technologies to Platforms: Structure of This Review

Following the vision of microwave technologies which enable wearable applications, our review starts by highlighting the key challenges and requirements of wearable devices before progressing to reviewing the research progress to fulfill these requirements. This review is comprised of three main sections, as in Fig. 1.

First, the three main enabling technologies themes are reviewed in Section III, which can be broadly classified into three main challenges [2]:

1) **Power**: Microwave-enabled energy harvesting, covering wireless power transfer and ambient energy harvesting techniques.
2) **Communication**: Low-power and passive communication, including backscattering transponders and energy-aware systems.
3) **Sensing**: Near- and far-field RF sensing techniques including RFID and novel readout circuits.

The review then deals with the physical implementation and integration platforms of such technologies, towards wearable applications, in Section IV. Passive components (e.g. antennas, filters, and interconnects), sensors, and packaging approaches as well as semiconductors ranging from discretes to Complimentary Metal Oxide Semiconductor (CMOS) system-on-chips (SoCs) and natively-flexible semiconductors are discussed, as summarized in Fig. 1.

Finally, the review progresses to laying out a future roadmap of microwave research towards propelling the next generation of wearables, in Section V. Healthcare applications are highlighted as a key stream, in Section V-A and the overall interdisciplinary sustainability and material challenges are holistically outlined, with a speculative outlook on the anticipated research trends and novel cross-topic application areas.

TABLE 1. Related reviews and their main focus.

Review	Focus areas
This review	1. microwave enabling technologies; 2. materials and integration platforms; 3. applications and research roadmap
(2017-2022) [3], [4], [5]	**Wearable systems:** Healthcare applications
(2018–2022) [6], [7]	**Wearable systems:** Holistic and energy autonomous wearable sensor nodes
(2021–2022) [8], [9]	**Enabling Technologies:** Backscatter communications
(2013–2022) [10], [11], [12], [13], [14]	**Enabling Technologies:** RFID and RF-based sensing
(2013–2022) [15], [16], [17], [18], [19], [20]	**Enabling Technologies:** Far-field wireless power harvesting and rectennas

B. Requirements for Wearable Devices

Wearables have found their way into our daily lives and the projected revenue of the wearables industry is expected to grow rapidly in the coming years. However, the actual revenue has been lagging behind the projected growth in recent years. Fig. 2 shows a few examples of commercial wearable devices, see [32]; these reveal some of the main issues hindering the growth of wearables industry. The size of today's most wearables is too big for integration into daily life. The requirements of wearable devices depend upon the application, but these typically involve monitoring an individual's biosignals e.g. electrocardiogram (ECG), other physiological parameters such as oxygen saturation level (SpO_2), activity levels e.g. the number of steps and movement and position on sports playing fields.

The consumer market is dominated by smart watches where many of these parameters can be monitored to a sufficient degree of accuracy [33]. Whilst they can provide some useful low-level medical information, factors such as motion artefacts and the location on an individual's wrist will compromise the performance and the quality of data captured [34]. Such factors will limit the range of applications that smart watches can be used for. Certainly, in the case of heart rate monitoring, improved signal and data quality can be

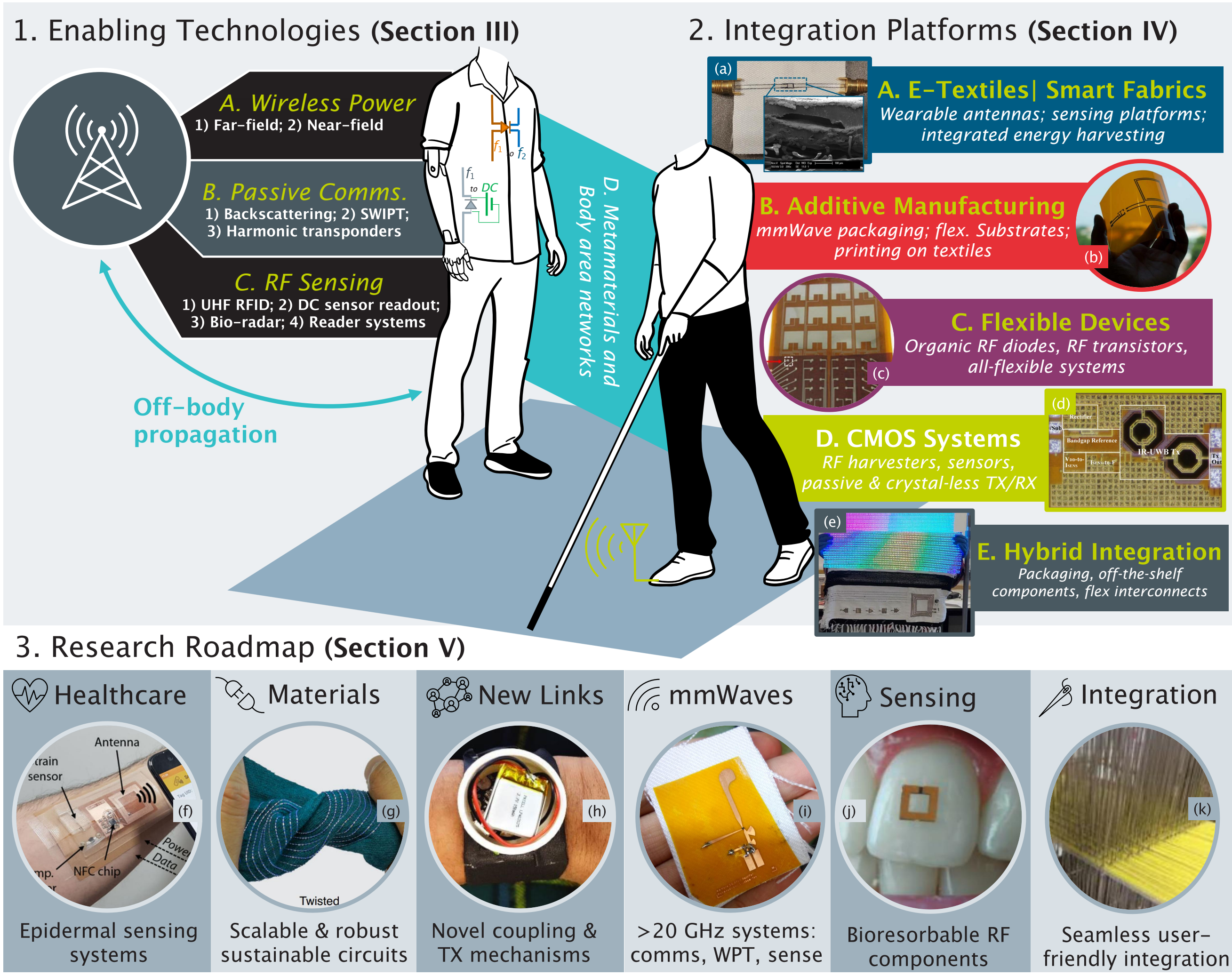

FIGURE 1. An overview of next-generation wearable systems enabled by microwave technologies as reviewed in this article. Sub-figure image sources: (a) mmWave textile-based lines [21]; (b) inkjet-printed wearable rectenna [22] (© IEEE 2015); (c) all-printed phased array [23] (© IEEE 2013); (d) wearable CMOS RF-powered UWB SoC [24] (© IEEE 2020); (e) multi-function textile [25]; (f) NFC smart bandage [26] (© IEEE 2021); (g) embroidered liquid metal RF textiles [27]; (h) body-coupled communication electrodes [28] (© IEEE 2020); (i) mmWave textile-based rectenna [29] (© IEEE 2020); (j) RF tooth monitor [30] (reproduced with permission, Wiley & Sons); (k) weaving flexible circuits into textiles [31].

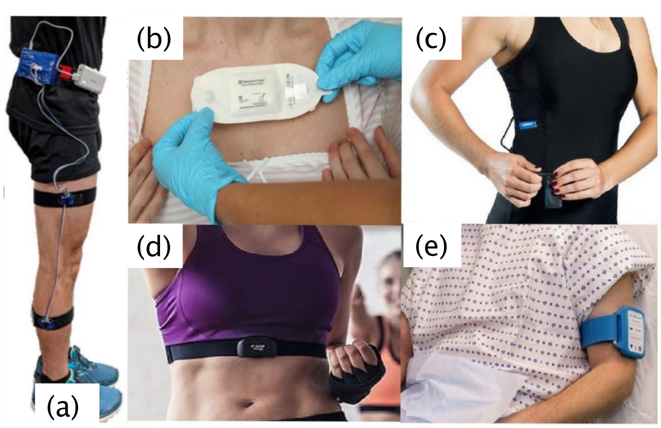

FIGURE 2. Current generation of commercially-available wearables: (a) leg movement sensors; (b) adhesive patch; (c) clothing with embedded sensors; (d) chest straps; (f) upper armband strap [32].

achieved from chest bands that use electrodes in contact with the skin to measure ECG directly. Chest bands are limited to two electrodes which are sufficient to monitor heart rate variability [35], but clinical quality ECG data requires a larger number of electrodes which can be achieved with smart clothing [36]. At present, commercially available smart clothing typically relies on conventional rigid electronic modules that are located within pockets manufactured within the garment (e.g. STATSports Apex) whilst some do integrate electrodes within the fabric (e.g. Hexoskin, Prevayl).

Clothing-based wearables, also known as smart textiles [4], electronic (e)-textiles [31], and smart fabrics, have the potential to revolutionize wearables as a ubiquitous, comfortable and familiar platform. However, this will require e-textile technologies to invisibly integrate the sensing, data processing, and communications functionality, realized using a range of platforms (Section IV-A to IV-E) within clothing

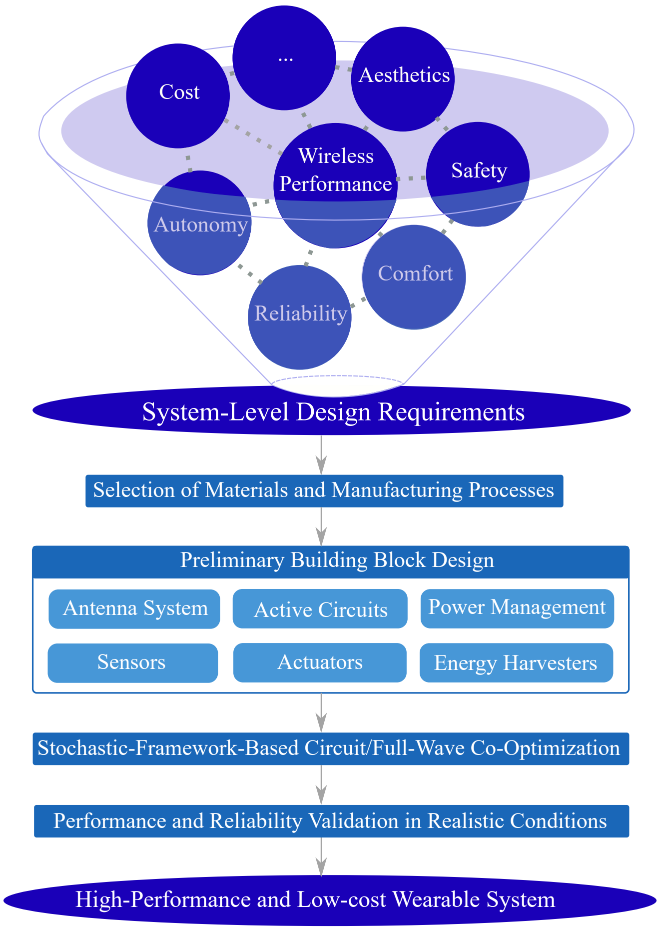

FIGURE 3. A holistic stochastic-framework-based design approach: from a complex set of design requirements to reliable, high-performance, and low-cost smart wearable systems.

in a reliable and robust manner (see section IV-E), to meet a large set of requirements highlighted in Fig. 3.

Irrespective of the platform, other application-specific factors constrain wearable technologies. The limitations of batteries and the associated finite operating time between recharging coupled with the inconvenience of recharging are an ongoing challenge for the technology. Convenient wireless powering techniques for directly powering systems or recharging batteries are highly desirable as are developments towards flexible and textile-based batteries that remove the reliance on conventional rigid batteries [37], [7], [38]. Long-term monitoring applications should also consider required data rates, the quantity of data and security requirements when wirelessly communicating [35], potentially enabling the use of passive communication [8].

C. Related Reviews

Across the spectrum of wearable technologies research, and RF IoT and body-centric technologies, there are several related reviews which can be highlighted. Table 1 summarizes the recent reviews which deal with the underpinning microwave technologies discussed in this work, as well as the wearable applications and integration platforms.

The existing reviews evidence the renewed interest in human-centric wearable electronics. Nevertheless, this review is the first to consider the challenges across the three themes of power, sensing, and communication, the practical implementation platforms, and the future interdisciplinary challenges from a holistic perspective.

III. Enabling Technologies

Power autonomy, communication, and sensing are three enabling roles of microwaves [2]. Undoubtedly, power is the key challenge in wearable systems. Diversifying the available power sources and minimizing the power consumption are the two pillars of tackling the power challenge in wearable devices. Therefore, the first two enabling microwave technologies reviewed are WPT, including energy harvesting, and low-power, approaching "near-zero power", communications. The third enabling microwave technology often combines WPT and low-power operation: RF sensing, where we review sensing devices, architectures, as well as associated readers required for interfacing with wearable RF-enabled sensors.

A. Wireless Power Transmission (WPT) and Harvesting

Tesla's dream of wireless power through resonance inspired a century of research into wireless power transmission. W.C. Brown's transition to focused microwave beams [39], later followed by Yoo and Chan's work on mmWave WPT [40], gave birth to rectennas, in their modern day form. Rectennas have already enabled a pervasive technology, RFID, to become a billion device industry; a feat that would be unattainable without RF power harvesting frontends in RFID ICs [16]. Here, we broadly classify WPT into far-field rectenna-based (over 100 MHz) and lower frequency (resonant and inductive) techniques, reviewing the recent advances and identifying shortcomings.

1) Rectennas and Far-Field Harvesting

The endeavour to bring far-field WPT to ubiquitous commercial use, beyond RFID applications, started in the early 2000s [41], [42], following the growing vision of energy harvesting-powered IoT [15], [17]. Shortly afterwards, the first wearable rectennas were demonstrated using textile antennas connected to rigid rectifiers [43] and fully-textile rectennas [44]. A later hybrid device combining high-performance rigid rectifiers and power management with a textile patch antenna showed that wearable RF energy harvesting could start at sub −20 dBm levels, but only when a low-loss substrate was used for the rectifier matching [45]. Wagih *et al.* then demonstrated that all-flexible textile-based implementations do not hinder an efficiency comparable to rigid systems, using a combination of lumped matching networks and antenna-rectifier co-design [46], [38].

Fig. 4 summarizes the progress in wearable rectennas and far-field energy harvesting systems. The first element in

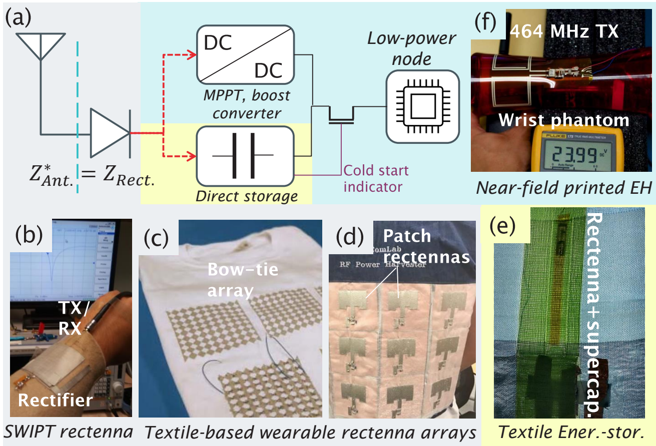

FIGURE 4. Progress in wearable far-field energy harvesting: (a) generic system blocks; (b) textile SWIPT rectenna [38], [51]; (c) screen-printed broadband array [48] (© IEEE 2020); (d) embroidered patch rectennas [47] (© IEEE 2019); (e) textile-concealed rectenna and supercapacitor [49]; (f) inkjet-printed flexible rectenna with rigid DC-DC power management and load [22] (© IEEE 2015).

Fig. 4(a), the rectenna, has been implemented in a wearable format in a plethora of studies [46], [38], [29], [47], [48], [44]. In fact, the aforementioned rectifier implementations on textiles matched to 50 Ω, e.g. [44], [47], [46], can be integrated with any wearable or textile antenna covering the same bandwidth. Yet, integrating the rest of the system in a wearable-friendly package remains a challenge. A rectenna integrated with a spray-coated cotton-based carbon supercapacitor has shown that far-field power reception using an all-wearable receiver can be an order of magnitude more efficient compared to other mechanical energy harvesters [49]. Nevertheless, the reported integration of wearable rectennas and DC-DC power management were limited to circuits implemented on rigid PCBs [50], [22], despite using textile or flexible antennas.

Wearable rectennas have been realized using antennas decoupled from the body using ground planes [43], [44], [45], [47], [51], and more recently using broadband, and hence detuning-resilient, antennas placed directly on the body [46], [48], [52]. The former offers higher off-body gain but requires electrically-thick substrates (>0.01λ), with the latter maintaining a lower profile and showing potential substrate-independence, due to the very wide bandwidth [52].

The aforementioned rectennas were mostly based on 50 Ω-matched antennas, and require a separate impedance matching stage between the antenna and the rectifier. Textile-based rectifiers [46] have been demonstrated with very comparable RF to DC efficiencies to their rigid low-loss counterparts [45]. However, there is always a desire to eliminate the impedance matching network, either for lower complexity rectennas, or for avoiding the insertion losses in impedance matching components, found even in highly-efficient rectifiers [53]. Therefore, antenna-rectifier co-design was recently implemented in textile rectennas for Simultaneous Wireless Information and Power Transfer (SWIPT) [38], [51]. A summary of the DC power output and efficiency[1] of reported flexible and textile-based far-field rectennas, at varying incident RF power levels, is shown in Fig. 5. It is evident that wearable rectennas do not lag behind their non-wearable counterpart in their efficiency and sensitivity, especially when compared to the benchmark rectenna included in the figure from [54]. However, the power output is ultimately limited to sub-mW levels, except for a large high-gain rectenna operating under a high-S illumination.

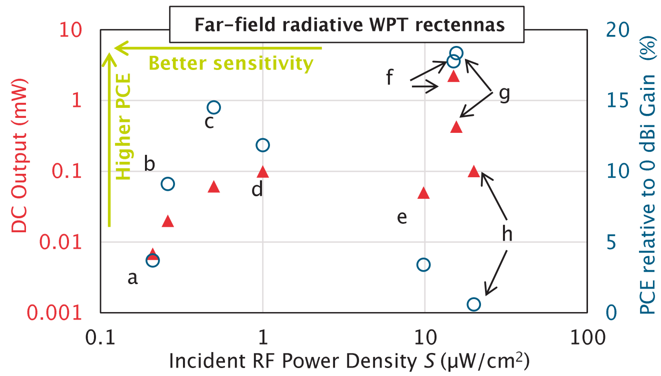

FIGURE 5. Comparison of recently reported far-field WPT rectennas implemented using wearable materials: a. [50], b. [46], c. [38], d. [54] (not wearable), e. [47], f. [44], g. [58], h. [48]. The exact values are provided in the article's dataset.

Wearable and flexible rectennas were not restricted to far-field operation, flexible and printed rectennas have been demonstrated harvesting up-link power in the near-field of phones [55] and two-way radios [22], [56]. In fact, an early spectral survey in a busy environment, i.e. a commuter train, found that the freely-available "recyclable" power in the up-link frequency bands was higher than that available from down-link [57]. Therefore, powering wearable rectennas from co-located high-power transmitters, e.g. phones, could be an alternative means of scavenging energy [22]; 5 s in close proximity with a transmitting 446 MHz (0.5 W) two-way radio was found to yield over 47 mJ [56].

2) Near-Field and Multi-Mode WPT networks

A key limitation of any body-centric far-field RF WPT or energy harvesting effort is the ultra-low power output. It was seen in [49] that the net DC energy output does not exceed milli-joules at less than four metres in the far-field region, at sub-1 GHz. To explain, it is critical in wearable WPT applications that the EIRP limits are observed, for the Specific Absorption Rate (SAR) to be kept within the IEEE

[1] The PCE is calculated using the DC output P_{DC} and the effective area $A_{0\ \mathrm{dBi}}$ of a 0 dBi antenna operating at the same frequency. The PCE was calculated at the incident power density S at which the efficiency approaches its optimum range using $\mathrm{PCE} = P_{\mathrm{DC}}/(A_{0\ \mathrm{dBi}} S)$. Using the gain of a 0 dBi antenna, the size of the wearable rectenna is not compared but the influence of the antenna is factored in the "PCE".

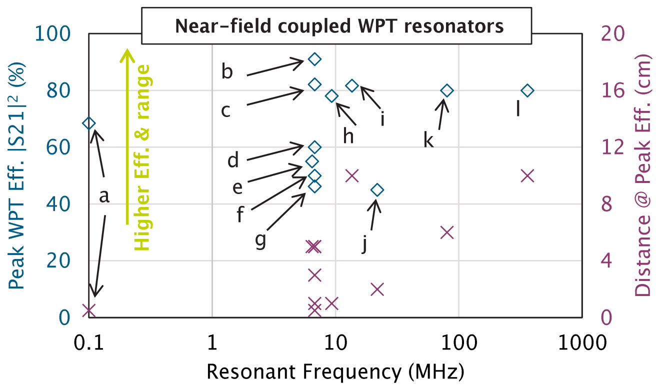

FIGURE 6. **Comparison of recently reported near-field WPT resonators implemented using wearable materials: a. [60], b. [68], c. [62], d. [69], e. [50], f. [65], g. [70], h. [71], i. [65], j. [72] (non-wearable), k. [73], l. [74], [75]. The exact values are provided in the article's dataset.**

C95.1 standard. Therefore, very high-power microwave WPT techniques, e.g. [59], cannot be directly used to meet the demands of power-hungry wearables. Therefore, two-coil near-field resonant inductive power transfer (IPT) and multiple-coil IPT (i.e. typically 3 or 4 coil systems), often referred to as magnetic resonant (MR) WPT are an attractive solution for providing high power levels to wearable devices. As near-field WPT offers a high link efficiency (S_{21}^2) at short ranges, Fig. 6 compares the peak efficiency and range of recently-reported near-field WPT efforts using wearable-friendly materials, where it can be seen that despite the high efficiencies, the range is often under or around 10 cm. The wireless range is directly linked to the coil/resonator's radius and its peak WPT efficiency is linked to the coupling coefficient and the Q-factor.

Following a comparison of fabrication methods of textile-based coils [60], Qi-standard circuitry were integrated with screen printed coils towards wearable IPT [61]. Embroidered coil, using Litz threads, typically have the highest Q-factor and lowest series resistance and parasitic capacitance [60], enabling them to achieve a high S_{21} [62]. Over-coupling can be a problem that leads to frequency-splitting in such high-Q coils with high coupling k values which can be mitigated adaptive tuning circuitry [63] or driving the transmitting coil with a constant current [64]. For wearable applications, the implementation of such circuits should consider the size, packaging, and complexity requirements for seamless integration in clothing.

On the other hand, MR WPT (i.e. multi-coil systems) can enable longer range of operation, and has been implemented using flexible coils towards on-body applications [65]. A measurement campaign was reported in [66] showing the impact of changing the receiving coil's on-body position, for a fixed link distance, and that an over 10 W power level can be received safely on most body parts around 20 MHz. Near-field WPT was also explored in large networks through textile-based waveguides which nearby wearables can couple to [67].

To overcome the limit of both low-power far-field and short-range near-field WPT, Hybrid near- and far-field rectennas have recently been developed. A broadband antenna with an integrated coil demonstrated that the presence of an inductive WPT coil can aid in the antenna miniaturization [50]. This effort builds upon existing applications in HF RFID systems integrated with UHF antennas [76]. The near-field WPT receiver could generate over 3 W DC output, with the potential for over 50 W reception with an SAR under 1.7 W/kg [77], based on a simple bridge rectifier implemented on a flexible substrate, representing over 100% improvement in the DC power output compared to prior Qi-based implementations [61].

B. Passive and Power-Autonomous Communication

Following the delivery of power using wearable-friendly materials, power-aware communication between wearable devices, with either on- or off-body devices, is the second key role of microwaves. This section provides an overview of the emerging advances in passive and low-power communication and their potential applications in wearable body-centric networks.

1) Low-Power Communication, Backscattering, and Software-Defined Readers

Passive communication using backscattering transponders has enabled a plethora of applications ranging from sensing [8], [10] to high data-rate communication [83]. The ultra-low power consumption of backscattering modulators, due to the lack of carrier generation or amplification leads to wide-scale adoption of backscattering in energy harvesting and energy-constrained systems [84].

With the evolution and foreseen rapid deployment of wearables, the adaptability of backscattering systems is increasingly important. In the case of RFID backscattering, which are now ubiquitous, readers and transmitters have significantly evolved. Software Defined Radio (SDR) is one of the most used technologies to make RFID readers more adaptive and easier to integrate. Using SDR, it is possible to abolish the constant need to change hardware and to change the core properties of the backscattering receiver only through software. Ref. [85] presents a design and implementation of an RFID reader based on a low-cost SDR and open-source resources to overcome hardware limitations. Fig. 7(a) shows the key blocks an RFID reader front-end. The SDR platform in [85] has increased the detection range of the tags to 6 m.

In [86], SDR technology was combined with multi-sines to increase the power delivered to passive sensors and the receiver sensitivity. It is possible to find other types of RFID systems based on SDR technology applied in several situations, such as research [87], localization [88], or even industry. Low-cost fully-integrated backscattering tags were recently reported based on digital modulation such as Pulse-Amplitude Modulation (PAM) [89], [80].

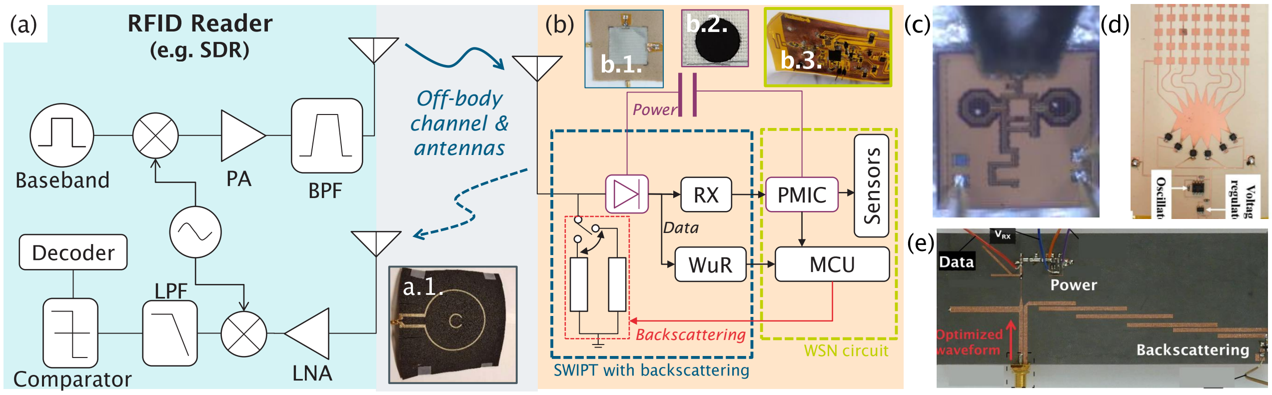

FIGURE 7. **Backscattering and SWIPT circuits: (a) RFID reader block diagram (a.1. a wearable RFID reader antenna, © IEEE 2019 [78]); (b) a SWIPT backscattering WSN (b.1. a textile SWIPT rectenna [51]; b.2. a textile supercapacitor [49]; b.3. a flexible wearable WSN, [79], © IEEE 2019); (c) a 4 mm^2 digital backscatter tag IC [80] (© IEEE 2021); (d) a solar-poweerd flexible beamforming backscattering tag [81] (© IEEE 2020); (e) a SWIPT receiver with backscattering [82] (© IEEE 2022).**

The approach to decoding is similar in both cases because the signals received from the two-backscatter modules are modulated in amplitude. In the case of the first module, after initial signal processing, two dynamic thresholds are set so that it is possible to decode the two different bits. When the modulation received is 4-PAM, the approach is similar. The difference is that four levels of dynamic thresholds are set. The demodulation becomes more difficult because the decision thresholds are not clear as the previous ones due to the noise present in the received signal. A fully-integrated digital backscattering tag is shown in Fig. 7(c). Moving to fully-integrated systems could enable wearable backscattering to operate in the mmWave spectrum; the antenna miniaturization will then enable novel topologies such as beamforming RFID tags for an improved read-range; a flexible beamforming tag utilizing a lens is shown in Fig. 7(d).

In harsh electromagnetic (EM) environments, e.g. ultra-compact wearables or even implants, backscattering transponders face a unique set of challenges. Backscattering is a widely adopted technique for telemetry in implantable applications since it results in extremely low-power consumption [90]. For example, in [90], the transmitted data pattern is used for load shift keying (LSK) modulation of the WPT coil and alters the reflected signal to an external reader. Despite achieving superior energy efficiency over active communication, backscattering radios fail to address the main requirements of mm-sized wearables/implants. Due to the small size of the power coil and a strong power carrier, which acts as a blocker, detection of the reflected signal on the reader side may be difficult or even impossible [91], [92]. In addition, modulating the power coil disrupts the power flow into the system and degrades power-transfer efficiency. Furthermore, the communication bandwidth of backscattering radios is often very low due to the high-quality factor (Q) of the power coil that limits the data rate.

On the other hand, active TRXs do not face the fundamental challenges of their backscattering counterparts and can potentially achieve high data rates at the expense of higher power consumption [92], [93], [94]. Considering the stringent power budget in implantable applications, the main design goal is achieving the highest possible energy efficiency; hence, proper modulation schemes should be chosen. It is well known that there is a trade-off between energy efficiency and spectral efficiency in communication systems [95]. Narrow-band modulation schemes demand a relatively complex architecture to generate an accurate frequency whereas wideband modulation schemes such as on-off keying (OOK) have often less complexity and result in higher energy efficiency.

2) Dynamic and Wearable SWIPT Systems

Numerous promising systems have been proposed to implement simultaneous wireless information and power transfer (SWIPT). In this case, the SWIPT paradigm presents a realistic answer to the need for energy-efficient and battery-free devices in industrial applications, where node maintenance is the most challenging task.

When considering SWIPT-powered IoT sensors, shown in Fig. 7(b), we essentially see three phases in the communication protocol: an Energy Harvesting phase (EH), a DownLink (DL) communication phase, and an uplink BackScattering phase (BS). The signal can be decoded thanks to the non-linear characteristics of the diode(s) in the energy harvesting part. Then, it is possible to interpret the information employing the same rectifying circuit without the need for a power-consuming local oscillator [84]. The battery-free sensor node contains BS module, energy harvesting, wake-up receiver, power management unit, and processor [96].

In [97], the idea of a battery-free wireless sensor, based on an intelligent mesh sensor network, for structural health monitoring applications in harsh environments was proposed. In the physical world, the sensing nodes send the collected data, temperature and humidity, to the communicating nodes through the Internet, using a long-range wide area network uplink communication, a battery-free wireless sensing node was designed based on SWIPT. In [98], [99], authors have optimized another essential aspect of being considered for SWIPT, achieving higher PCEs while increasing the information rate. The FSK modulation technique in [98], [99] employs multi-tone signals with different frequency spacings between the tones within one symbol to increase the amount of information per symbol, thus improving spectral efficiency and data transmission.

A voltage-doubler rectifier was designed to harvest Bluetooth Low Energy (BLE) packets for SWIPT in [100]. Adding an inductor to the output of the voltage doubler, playing as a diplexer, isolates the DC current aimed for energy harvesting from frequency-modulated information current. A later effort reported a high energy harvesting efficiency, similar to continuous wave signals, from sub-1 GHz FSK packets generated using a commercial IoT transceiver enabling battery-less cold-start of a sensor node [101].

In an application for wearables using dual-band SWIPT, [38] presents a textile antenna that communicates at 2.4 GHz and rectifies at sub-1 GHz. The rectenna, which uses conductive fabrics on a felt substrate, achieves a high power conversion efficiency of 62% in energy harvesting, not affecting the communication performance. However, using two separate distant frequency bands for power and information transfer decreases the system's spectrum efficiency. Nevertheless, it improves the isolation over an in-band implementation using a similar antenna design [51].

A further step forward is provided in [82] and [105], where the a combined SWIPT/third-order intermodulation (IM3) backscattering architecture was presented; the demodulator/harvester is shown in Fig. 7(e). The design, combining an energy harvesting circuit with backscattering, is capable of simultaneously harvesting wireless RF energy and transmitting data to the base station. Consequently, the design consists of two parts: a rectifier based on harmonics termination and a branch consisting of a bandpass filter and circuitry to manipulate the impedance seen by the diode and antenna at the desired frequencies. Based on such a frequency division duplex (FDD) architecture, energy is harvested at one frequency (f_{EH}) and reflected at the other frequency, f_{BS}. A three-tone waveform is designed to improve both the PCE of the energy harvesting part and the strength of the received information signal. The described SWIPT BS system can enable the next generation of power-autonomous wearables. For instance, the insets in Fig. 7(b) show various wearable-friendly implementations of its building blocks.

3) Harmonic Transponders

Wearables operate in a highly varying EM environment that is particularly prone to strong fading as well as interference. Harmonic transponders belong to a special category of tags based on backscatter communication, which excel for robustness and low cost. A typical harmonic backscattering system is shown in Fig. 8(a). A harmonic tag is interrogated by the reader at the fundamental frequency f_0, and responds at a multiple frequency of the received fundamental tone (i.e., at $n \times f_0$, where n is an integer ≥ 2) [10], [106].

The harmonics are generated by non-linear components; generally, a single low-barrier Schottky diode or a frequency multiplier is used. Unlike traditional backscatter radios, where a bias signal is used to drive a switch to modulate the interrogating signal, harmonic transponders operate without any DC signals and with very low RF input powers (< -30 dBm) [107]. The simplest harmonic tags provide a single bit of information (the presence or absence of the tagged object), making them suitable for article-surveillance and tracking applications [108]. Transducers can be included in the transponders to introduce sensing capabilities, either at the input or at the output of the frequency multiplier. Fig. 8(b) shows a harmonic modulator loaded with piezo-resistive sensor, based on a Schottky diode, with a fully-integrated CMOS transponder shown in Fig. 8(c).

Harmonic transponders have numerous advantages over more classic wireless transceivers. The first aspect is that, since the tag can be passive and consists of a simple circuit, it does not require a DC power supply, and it can be very small in size. Both features are particularly attractive in wearables as they simplify the packaging [109], and reduce the points of failure [110]. Furthermore, since the receiver of the reader is tuned to the n-th harmonic channel, it is not affected by ambient reflections (which occur at f_0), which makes the system immune to the clutter phenomenon and suitable for harsh environments [111].

In a conventional passive (i.e., RF-powered) RFID system, the tag's range is often limited by the sensitivity of the rectifier. In energy harvesting or battery-assisted RFID tags [112], the read range is limited by both the energy available at the tag and the reader's sensitivity. Unlike traditional backscatter transponders, the read-out distance of harmonic tags is typically not limited by the minimum power received by the tag, but rather by the sensitivity of the reader's receiver, i. e., by its capability to detect low-power RF signals at the harmonic frequencies. Generally, the receiver is tuned to the second harmonic, since the latter is characterized by the minimum conversion loss C_l of the tag, defined as the ratio of the available power at the input of the frequency multiplier to the power delivered to the load at a harmonic frequency.

The power of the received second harmonic P_{rx}^{2f0} can be estimated using a link budget analysis as follows:

$$P_{rx}^{2f_0} = \frac{1}{4}\frac{P_{tx}^{f_0} G_1^r G_1^t G_2^r G_2^t}{C_l}\left(\frac{\lambda_0}{4\pi d}\right) \quad (1)$$

where P_{tx} is the transmitted power at f_0, d is the tag-to-reader distance, and G_i^j i the specific antenna gain ($i = 1$ fundamental, $i = 2$ 2nd harmonic, $j = t$ tag, $j = r$ reader). C_l is the key parameter of a harmonic transponder, since it significantly affect the read range of the tag.

Fig. 8(d) shows an example of a commercial harmonic transponder from RECCO™ [113], where it is used as a

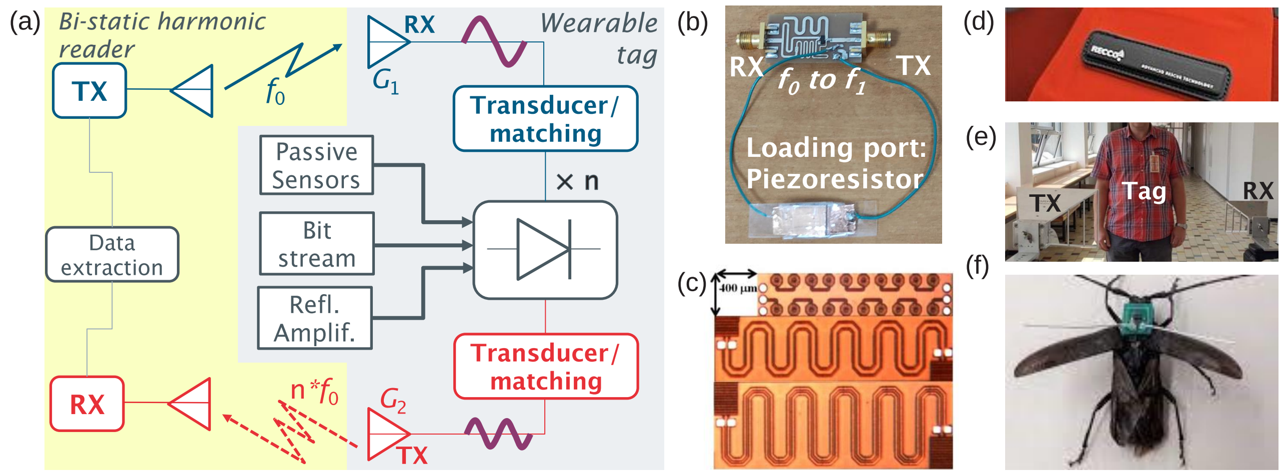

FIGURE 8. Harmonic backscattering systems approaching wearable applications: (a) operation principle [10]; (b) a sensor-loaded PCB modulator [?]; (c) fully-integrated harmonic transponder [102] (© IEEE 2010); (d) a commercial avalanche rescue RECCO™ tag based on harmonic backscattering; (e) off-body interrogation of a wearable harmonic tag [103]; (f) "wearable" harmonic tags for insect tracking [104] (© IEEE 2020).

safety feature in ski suits and accessories. Being a clutter-robust system, in the event of an avalanche, it can be used to identify the position of the person buried under the snow. A recent example of a wearable harmonic tag can be seen in Fig. 8(e). Extending "wearables" beyond humans, another interesting application made possible by the small size and conformability of harmonic tags is insect tracking. Harmonic tags have been applied to study the behavior of even small insects, such as grasshopper [114] or flying deer, as in Fig. 8(f) [104]. The tag is directly mounted on the insect and is designed to not interfere with the insect motion.

Future developments of this technology are following two main lines. On one hand, efforts aim to extend the read-range of harmonic tags, improving its conversion loss at very low RF inputs. For example, low-power reflection amplifiers, based on tunnel diodes, have been used to achieve an 18 dB conversion gain with a power consumption of 144 µW and a DC bias under 200 mV, showing great promise for long-range backscattering [115]. On the other hand, harmonic tags have been integrated with sensors, thereby providing additional useful information, as shown in the piezoresistor-loaded transponder in Fig. 8(b). In [116], a frequency doubler for pressure sensing was reported. The magnitude of the backscattered second harmonic depends on the applied pressure to a piezoresistive slab. The piezoresistor is inserted at the output matching network of the frequency doubler and controls the level of the DC voltage which make the sensor reverse biased, thereby varying the magnitude of the backscattered second harmonic [116]. Similarly, the matching network could be loaded using a switch driven by an encoded bit-stream [117], enabling the harmonic modulator to carry more information in a clutter-free, dual-band, and bi-static manner, which could be particularly attractive for fully-integrated transponders, e.g. Fig. 8(c).

C. RF Sensing and RFID

While radar is a very well-established microwave technology, RF sensing continues to attract research interest due to its potential to observe new biological parameters, or to significantly reduce the complexity of sensing systems. This section reviews several advances in wearable RF-based sensing including antenna and tag design, their applications, as well as read-out circuits and integration with other components in the challenging EM environment in which wearables operate.

Starting with UHF RFID, as a well-established commercially-available platform, single- and multi-parameter sensing are reviewed. Examples of new readout circuits including RF to DC conversion techniques for sensing are then discussed. We then review contactless RF sensing techniques based on smart textiles. This section concludes by introducing recent advances in RFID readers and their tuning methods, which can support the aforementioned applications operating in the electromagnetically challenging body-centric environment.

1) UHF RFID: From Identification to Multi-Port Sensing

Ultra High Frequency (UHF) RF IDentification (RFID) in the 860–960 MHz band is a well-commercialized technology. UHF RFID is a scalable technology that offers moderate operation distances using compact transponders [13]. RFID antennas can now be mass-manufactured in any shape and material, including plastics, paper, washable e-textiles [109], [121], and elastomers, so that they can be integrated within medical-grade tapes and bandages [122], or directly attached to the human skin. Measurements of physiological parameters such as temperature, pressure, and moisture are now feasible with commercial-off-the-shelf (COTS) tags. More experimental devices also involve sensing of chemical parameters (e.g., pH, chlorides) [123] and bio-electric signals (e.g., ECG, EMG, skin resistance) [124].

As a further improvement, multiple functionalities can be compressed on the same device. Indeed, the number

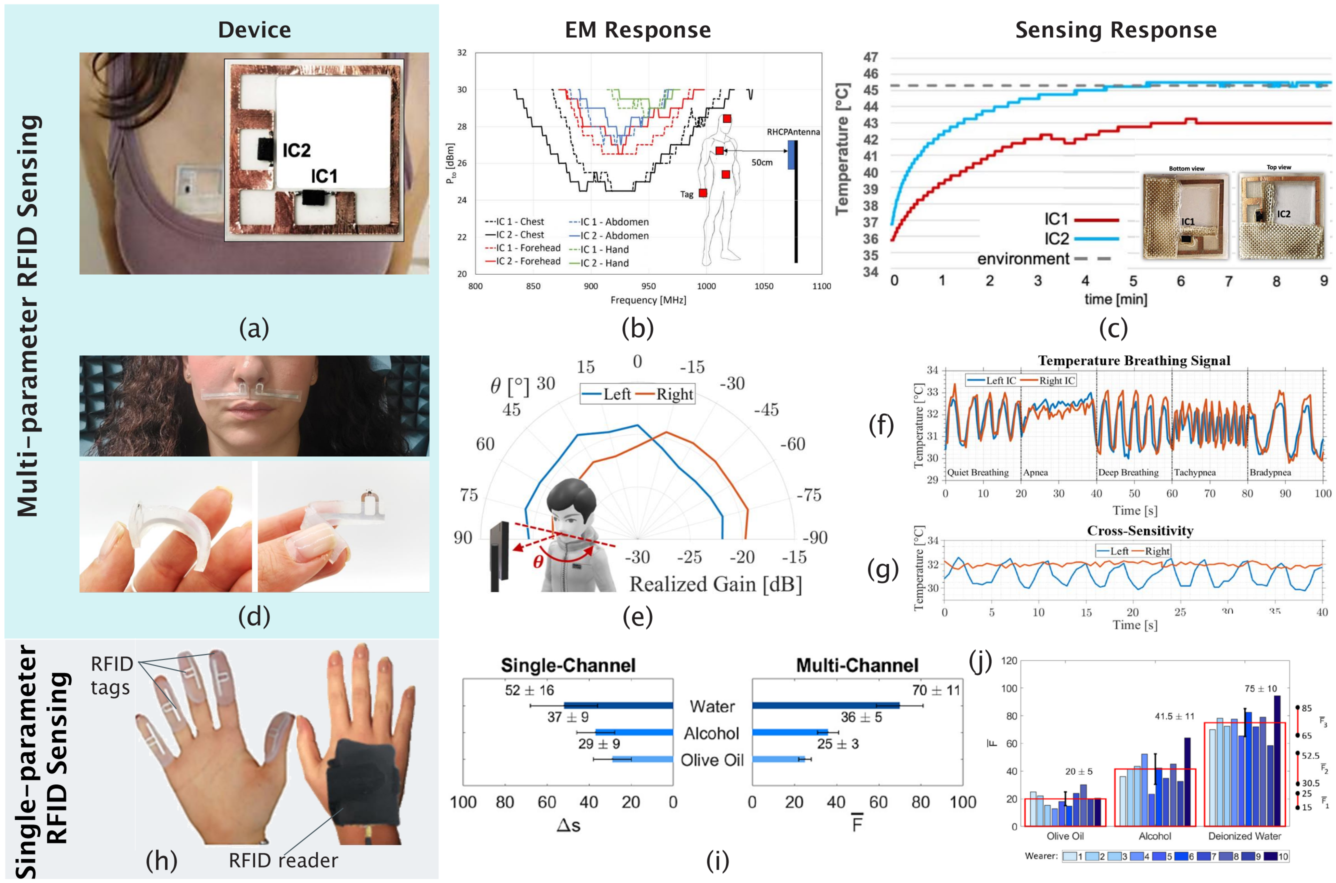

FIGURE 9. **Wearable RFID-enabled multi-parametric sensing of the skin (a, b, c), ambient temperature (© IEEE 2020 [118]), and (d,e,f,g) nasal respiration [119]: (a) Dual-chip epidermal sensor made by carved copper onto a biocompatible silicone layer; (b) measured turn-on-power on different body regions; (c) example of dynamic measurement of skin (IC1) and external (IC2) temperature; (d) dual-chip epidermal breath sensor made by aluminum dipole embedded inside soft, biocompatible, and self-adhesive elastomeric compounds; (e) measured realized gain at 870 MHz; (f) temperature-based respiratory patterns; (g) temperature traces of the two ICs when one nostril (right) is obstructed. Single-parameter RFID sensing of bottle contents (h, i, j,) [120]: (h) Multi-channel R-FAD device; (i) comparison between single-channel and averaged multi-channel R-FAD; (j) averaged fingerprints of ten volunteers when touching three objects with increasing permittivity.**

of sensors that can be simultaneously controlled can be expanded by increasing the number of embedded ICs, thus yielding *multi-port RFID devices* [125]. They can be intended both as a cluster of single-IC antennas in close mutual proximity, or as a single antenna provided with a multiplicity of embedded ICs. The multiplexing of the collected sensor data is performed *on-the-air* by means of the IDentification Division Multiplexing (ID-DM), which allows managing many data at the same time, with the standard EPC protocol, on the basis of the ID of each IC.

A multi-chip systems can be considered as an N-port coupled network, whose overall performance is defined by a generalized expression of the realized gain of the n-th port[2] [125]:

$$\tilde{G}_n = 4\eta_0 R_{IC,n} |[\mathbf{Z}_\mathbf{G}^{-1}]_n \cdot \mathbf{g}|^2 . \qquad (2)$$

The roles of impedance matching, gain, and polarization are indistinctly enclosed in (2), but can be explicitly separated under certain hypotheses (e.g., symmetry, periodicity). Moreover, depending on the type of the established coupling (i.e., constructive or destructive), improvements over the single-port case can be achieved [125], as if each antenna was "helping" the harvesting of the other.

Sensing-oriented multi-chip RFID systems can work according to two modes: *(i) multi-parametric sensing*, in case all the ports operate independently and each one returns a meaningful data, or *(ii) single-parameter sensing*, in case all the ports coherently contribute to a single output data. Here, several examples of RFID-based wearable sensors using both approaches are reviewed, illustrating how RFID sensing could add new functionalities to wearables in a non-pervasive manner using bio-friendly materials.

Multi-parametric Sensing. *(a)* The dual-chip loop antenna, in Fig. 9(a), from [118] is the first demonstration

[2] η_0 is the impedance of the vacuum, and $\mathbf{g}$ is the column vector of the normalized gains referred to each port when the other is open-circuited. $[\mathbf{Z}_\mathbf{G}^{-1}]_n$ indicates the n-th row of the inverse of the system impedance matrix $\mathbf{Z_G} = \mathbf{Z} + \mathbf{Z_{IC}}$, with $\mathbf{Z}$ being the two-port system matrix that can be numerically derived from simulations, and $\mathbf{Z_{IC}} = diag(Z_{IC,1}, Z_{IC,2})$ the ports termination matrix.

of the possibility of doubling the sensing capabilities of RFID epidermal devices without affecting their size and radiation performance. Starting from a one-λ loop, two almost-orthogonal current modes are excited by placing the ICs in the middle of two adjacent sides (by means of T-match impedance transformers). In this way, a dual-mode epidermal antenna is achieved, having equal radiating performance (and hence same read distance) for both the ICs (Fig. 9.b), even when tested onto different body regions. As an application example (Fig. 9.c), the temperature sensors embedded into the ICs (EM4325) were exploited to independently measure skin temperature (IC1) and ambient temperature (IC2). *(b)* Another dual-chip epidermal device, in Fig. 9(d), with symmetrical and stable on-skin performance, in Fig. 9(e), was recently presented in [119]. It is a two-channel flexible sensor designed to fit over the prolabium for the wireless and low-invasive monitoring of nasal breathing. The multi-parametric sensing, this time, is exploited to independently monitor the two nostrils by means of the embedded temperature sensors in the ICs (Axzon Magnus-S3). The rhythmic sequence of inhalation and exhalation during breathing produces temperature waveforms, in Fig. 9(f), that are well correlated to typical respiratory patterns. The measurements at the two nostrils were proved to be independent, in Fig. 9(g), so that possible left/right asymmetries between the nostrils can be reliably detected.

Single-parameter Sensing. Multi-channel RFID epidermal sensor-devices can also be used as an interface to the outside world for the emerging Tactile Internet [126]. This is the case of RF Finger Augmentation Devices (R-FADs) that are attached to the fingers and communicate with a body-worn reader. In [120], auto-tuning RFID microchips [127] are embedded in soft and flexible sensor-tags as in Fig. 9(h) to operate as dielectric probes that can help visually-impaired people in identifying the material of touched objects. The sensorization of all the fingers of the hand allows achieving a 100 % reliability of dielectric identification of the touched objects, as in Fig. 9(i) to discriminate among low-, medium-, and high-permittivity materials, shown in Fig. 9(j), with negligible influence from the interpersonal variability.

2) RF Sensing Wearables with a DC Readout

In addition to UHF RFID tags, several systems can be used to read-out the response of wearable RF sensors. Self-Injection Locking (SIL) sensors are among the topologies widely used in biomedical RF sensing [128], [129], [130], [131], [132], [131], [133]. Injection-locked self-oscillating antennas [131] or resonators [130], [133] may be applied to detect chest movements, or skin-surface variations of the fingertip or the wrist artery, enabling pulse detection. For example, a wearable RF sensor for breath rate detection is described in [128], making use of the SIL radar technique at 5.8 GHz, and combining it with a DC readout circuit.

This sensor, depicted in Fig. 10(a), is able to detect a subject's inhalations and exhalations; it consists of a 5.8 GHz dual-port aperture-coupled fed patch antenna, connected to

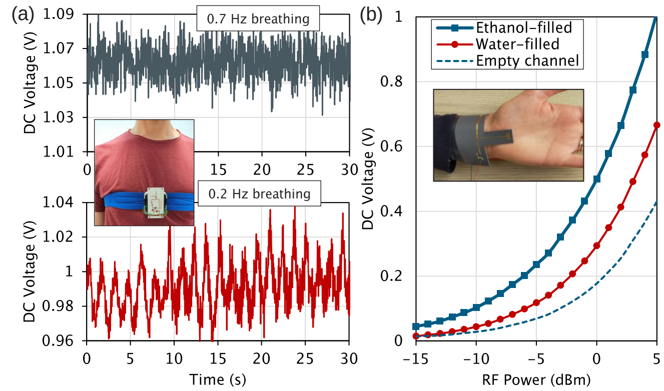

FIGURE 10. DC voltage-based readout of wearable microwave sensors: (a) SILO breathing sensor showing the breathing rate [128] (inset © IEEE 2022); (b) ethanol-detection filtenna at different power levels [134] (inset © IEEE 2021).

the input and output ports of a self-injection locking oscillator (SILO) based on a pseudomorphic high-electron-mobility-transistor (PHEMT) through dedicated gate and drain matching networks in microstrip line technology. As part of the oscillator feedback resonant network, the antenna itself acts as the sensor, being loaded by the human body. Thus, its resonant behavior varies with respect to the effective distance from the body. The device, that can be referred as self-oscillating-injection-locked loaded antenna (SOILLA), has a small footprint, is fully wearable, and can be worn by the user in the chest position at a specific distance from the body. With an output power of 13 dBm, the SILO's output can be detected off-body.

The oscillator output is coupled to a detector, which acts as the on-board demodulator so that the prototype does not require a dedicated receiving station and operates with no need for anchor nodes or remotely synchronized receivers. The same detector can act a RF-to-dc rectifier to harvest part of the energy to feed an MCU and a low-power radio to wirelessly transmit the sensor data. The SOILLA is validated through measurements of the voltage at the demodulator output, registered by an oscilloscope for two different types of breath tests: normal breath (about 15 breaths/min), and fast breath mimicking a condition of tachypnea (42 breaths/min) shown in Fig. 10(a) and (b), respectively. Finally, the proposed system can send in real-time wirelessly breath rate data to a computer, phone, or smartwatch via a system-on-a-chip (SoC), which can be fed by a portion of the RF energy coming from oscillator output via energy harvesting techniques.

Antenna/rectenna-based sensing represents another approach. A wirelessly powered wearable sensor designed to detect the presence of ethanol solutions [134] is shown in Fig. 10(b) where a filtenna (filtering antenna) is connected to a rectifier. The system is built on a Rogers Corp. RT/Duroid 5880 substrate (ϵ_r = 2.2, tanδ = 0.001 and thickness: 0.508 mm), which is flexible enough to make it wearable.

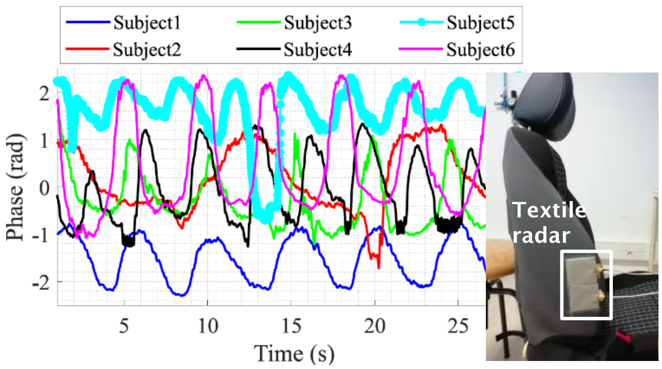

FIGURE 11. Breathing monitoring using a *bio-radar* integrated with textile antennas in a car seat application [136].

First, a resonant open stub is designed at 2.45 GHz, whose end is loaded by a microfluidic channel, and it is tuned to open resonate when the channel is filled with an ethanol solution of 70% concentration. The stub undergoes a drastic frequency shift of its input impedance when the channel content is substituted with water or when it is left empty. A frequency selector, consisting of a second-order open-end coupled-line filter, with one open end substituted by the loaded stub, is fed by the received power of a 2.45-GHz narrow-band patch antenna, allowing safe detection of the searched target fluid, with a consequent performance degradation for different channel contents. A full-wave rectifier based on low-threshold voltage diodes is used for signal transduction: fluid detection is read out by means of the different values of output dc voltages [134].

The entire system is co-designed by means of EM and nonlinear co-simulation [135]. This results in real-time feedback about the presence of the ethanol solution. The measured prototype validates this new RF sensor concept: Fig. 10(b), shows the measured output DC voltages with respect to the RF power received by the antenna, for different microfluidic channel fillings. The measurements, carried out on a human hand in a real environment, clearly demonstrate that an ethanol solution is distinguishable from other fluids [134].

3) Bio-Radar in Wearable Applications

Radar systems can capture vital signs, such as respiratory and cardiac signals, without requiring the usage of contact sensors or electrodes. Generally, based on the Doppler effect, these systems transmit EM waves towards the subject's chest wall, which are subsequently reflected and received by the radar. The chest-wall displacement changes the traveled path of the EM waves, which is perceived as a phase modulation on the received signal and it contains the vital signs information [137].

This system, referred to herein as the *Bio-Radar* system, presents multiple applications, enabling continuous monitoring which can help sense differences in the patterns of the vital signs and thus help identify sudden events, such as the drowsiness of a vehicle driver or the apnea of an infant during sleep time [137]. It is also possible to monitor bedridden patients in a critical state and possibly help in a diagnosis. Applications in psychology are also feasible, such as the measurement of the stress response [138], or even performing emotion recognition [139].

Leveraging wearables and semi-wearable integration, bio-radar applications might require a full set-up integration in customized objects. This enhances the low-profile character of the main system, streamlines the industrialization process, and provides more comfort for the subject being monitored. This can be accomplished by developing smart wearables, where the final user is the target object. In order to verify how this could be accomplished, a specific case study is reviewed. A bio-radar prototype was integrated into a vehicle seat upholstery to monitor the driver's vital signs, as shown in Fig. 11 [136]. This can also be applied to other applications, for instance, to monitor the other vehicle occupants and aircraft passengers, or adapted to monitor infants. Integrating textile antennas, not directly mounted on the body, extends the applications and remit of "wearables" to cover (e-)textiles found in the proximity of the user.

In the Bio-Radar context, antennas are the system element that stipulates the line of sight between the radar and the target. Therefore, their full integration in the application objects is a possible solution to enable the overall system concealment. To accomplish this goal, textile antennas might be used [140]. However, the bio-radar performance cannot be compromised and the quality of the signals must be kept accordingly. Therefore, for this specific case study, it is required to choose the appropriate location for the antennas considering the target population and the chest-wall expansion. In [136], the side lumbar support of car seat was the selected location since the side expansion of the chest wall can be measured.

Subsequently, the usage of fully-textile antennas in the bio-radar framework operating at 5.8 GHz was validated by acquiring the respiratory signal of one subject while seating in a car seat as depicted in the inset of Fig. 11. An additional validation step was performed by acquiring the respiratory signal of six different subjects, with different physical statures, without adjusting the antennas position. Considering the same signal duration (30 seconds), it was possible to distinguish different characteristics among the detected signals, seen in Fig. 11. For instance, signals present different respiratory rates, where the subject 2 presented a lower respiratory rate, and subject 4 presented a higher one.

4) RFID Readers and System Integration

Given the variability in a dynamic wearable environment, RFID readers for RF sensing-equipped wearables need to provide a dependable system operation despite a varying wireless channel and a harsh RF environment, i.e., the human body [141]. One possibility to ensure a dependable wireless operation is to include a real-time adaptive matching system at the reader. Such a system is detailed in this section

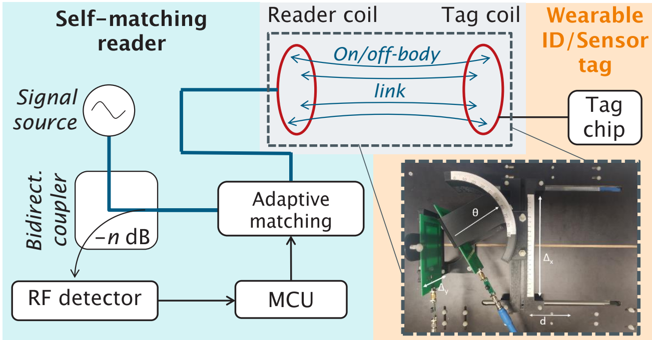

FIGURE 12. Self-tuning adaptive RFID reader; the photograph shows a semi-automated measurement-driven setup for training an auto-tuning reader.

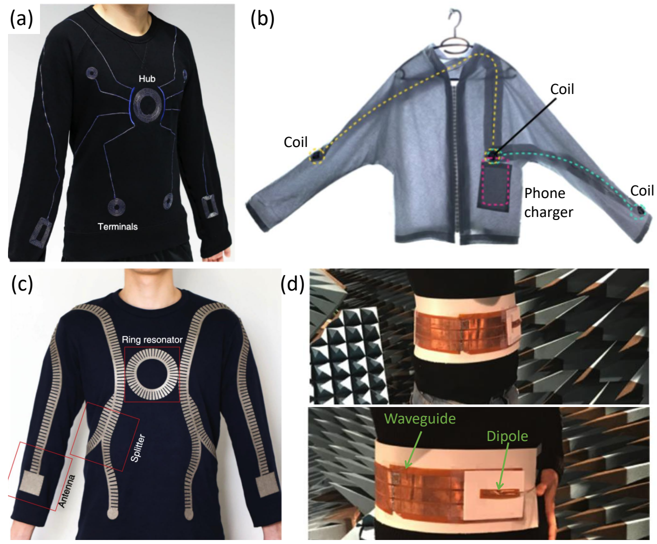

FIGURE 13. Body area networks (BANs) based on NFC: (a) Photograph of near-field-enabled long-sleeved shirt comprised of a network with a single hub and eight terminals [147]; (b) proof-of-concept NFCe jacket. The wireless signals can propagate through intricate pathways with NFC relays [148]; and based on metamaterials: (c) metamaterial textile network integrating splitters, antennas, and a ring resonator, ©Springer Nature 2019 [146]; (d) Wearable waveguide surface placed around the human body, ©IEEE 2021 [149].

for a magnetically resonant-coupled High-Frequency (HF) RFID system. Another possibility to ensure a dependable operation is to verify the RFID system in its dedicated application environment [142], using sophisticated software-defined-radio-based reader devices if necessary [143]. In addition, tests are required to ensure that the reader and the tag – the complete RFID system – follow the existing standards. Standard compliance is confirmed by using dedicated RFID test systems, as described below, additionally evaluating the devices' system performance.

A resonantly coupled HF RFID system will not operate optimally if one coil antenna changes its position relative to the other. Thus, researchers have started integrating real-time adaptive matching systems in the reader devices to achieve optimal power transfer for varying coil arrangements [144], [63]. An exemplary adaptive matching system, including details, is shown in Fig. 12. Variations in the coils' positions change the reader coil's input impedance, impairing WPT and communication. This impedance change can be re-adjusted by adapting the matching network connected to the reader coil. To realize real-time functionality, the adaptive matching network is controlled by an MCU using an optimization algorithm based on a deep neural network. The algorithm adjusts the matching network capacitance values to optimize the power transfer for the present coil arrangement. The inset of Fig. 12 shows the setup for measuring the coils' s-parameters and generating data for neural network training and testing. The coil dimensions correspond to Class 1 of the ISO/IEC 14443 standard.

RFID test systems are an inherent topic for RFID device and system development. For that reason, all RFID air interface standards are published together with conformance test standards, for example, for passive coupled HF systems (ISO/IEC14443, ISO/IEC10373-6, commonly referred to as NFC systems) and passive UHF radiative RFID (RAIN) systems (ISO/IEC18000-63, ISO/IEC18047-63). In particular, for UHF systems, the conformance test for basic certification is extended with performance standards for systems, readers, and tags (ISO/IEC18046-1 to ISO/IEC18046-3). System design for UHF RFID, in particular, relies on performance testing. Two parameters are essential for the reader RFID test systems, i.e., the maximum reader transmitter power, limited by radio regulations, and the reader receiver sensitivity. An example test system would be the UHF RFID CISC RAIN Xplorer test system. Next to the tag sensitivity, the reader transmitter power defines the RFID system's forward link performance [141]. The reader receiver sensitivity characterizes the backward link performance next to the tag's backscattered power. As tags work with less and less energy, the forward-link power range increases continuously, and the backscatter power does get smaller. This trend leads to the requirement of more sophisticated reader receivers with high sensitivity of −90 dBm shown in the latest product generations compared to −75 dBm of existing products, which enables the range and reading reliability of wearable RFID tags to be improved.

D. Metamaterials and Novel Body Area Networks

All the aforementioned enabling technologies feed into the effort of realizing Body Area Networks (BANs). BANs can be formed when two or more sensors or devices are worn on the body [145]; BANs include earphones, spectacles, headbands, watches, skin patches, clothing, and capsules. BANs can be used to transmit physiological signals from multiple sites to a central hub, which can compute vital health metrics unavailable to any single sensor and make the data available to clinicians and family members on the cloud. Such networks could therefore be used to develop a connected personal healthcare system that can deliver care outside of traditional clinical settings [146].

Creating body area networks requires practical and functional methods to interconnect multiple sensors distributed around the body. Wired connections are widely used in research and clinical settings to tether multiple sensors to a common hub, but are not suitable for continuous use during daily life. Currently, radio-based wireless communication is the standard method for establishing wireless connectivity between sensors. In this approach, signals from each sensor are radiated into the space around the body and networking protocols are used to eliminate interference. While reliable communication can be established, the efficiency and security of this approach is limited by the physics of EM radiation: the signal is obstructed by the body, leading to inefficient power use, and is vulnerable to eavesdropping attacks on personal data [146].

Wearable metamaterials provide the opportunity to overcome these limitations by using clothing as a platform to guide the propagation of signals. Metamaterials are artificial materials that have properties beyond the limits of natural materials made from elements structured at the subwavelength scale [150]. They provide unprecedented capabilities in manipulating EM waves and fields, and can in many cases be fabricated in flat, compact, and flexible formats. By integrating such metamaterials with clothing using conductive threads and fabrics, wearable metamaterials with broad capabilities across the radio-frequency spectrum can be realized [149], [146], [150], [151], [152], [153].

At low frequencies, wearable metamaterials can be used to establish power and data connectivity across the body via near-field communication (NFC). NFC is a wireless technology operating at 13.56 MHz that enables battery-free sensors to be remotely operated, but its utility for networking is limited by the need for the sensors to be in close proximity (at most a few centimeters) to the reader [147], [154], [148]. Clothing can be exploited to extend the range of NFC connectivity across the body by integrating inductive patterns to the near-field. Such clothing can be created by patterning conductive threads on existing clothing using computer-controlled embroidery [147]. Fig. 13(a) and (b) show examples of such near-field-enabled clothing designed to interconnect sensors at multiple distant sites around the torso to a central hub placed on the chest. Provided that the sensors are within about 3-4 cm of the inductive patterns, the clothing can reliably interconnect up to 6 sensors distributed across the torso, even during vigorous exercise.

An alternative design [148], features a twin meander coil encircling the torso tuned to resonance using a capacitor. This design, fabricated by knitting conductive threads, provides connectivity to sensors with dimensions of about 4 cm placed anywhere on the torso. When multiple inductor-capacitor resonators are chained together, they can form a magnetoinductive waveguide along which the signal cascades in manner analogous to a propagating wave. Using modular resonators consisting of a flexible planar coil and a slotted ground layer, tracks that crisscross the body, split into multiple tracks, and jump between different articles of clothing can be created [67]. The resonators are attached to existing clothing using vinyl and a heat press in a do-it-yourself process.

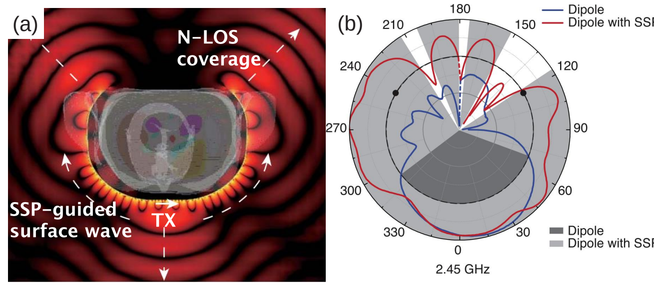

FIGURE 14. **Textile metmaterial-enabled omnidirectional NLOS coverage based on conformal propagation: (a) simulated E-fields around the body; (b) improvement over a single dipole antenna [151] (© IEEE 2020).**

Wearable metamaterials can also be used with standard wireless communication protocols in the GHz range, such as Bluetooth and Wi-Fi. Owing to the radiative nature of the signals, these protocols support long-range communication and high data rates, but require that each sensor is separately powered using a battery or an energy harvester. Metamaterials integrated into clothing can confine signals emitted by standard wireless devices to the surface of the body, which can reduce power consumption, extend battery life, and enhance security. The design of such metamaterials must balance efficiency and security, which requires that the signal be tightly confined, with the range of contact-less operation, which necessitates that the signal extend into the space around the body.

Metamaterial textiles that support surface plasmon (SSP)-like EM modes can provide a versatile platform for manipulating signal propagation. These textiles, which consist of conductive fabric sheets patterned with comb-like structures, can provide up to three orders of magnitude higher transmission efficiencies compared to conventional radiative communication and confine the signal to within 10 cm of the surface of the body [151]. Alternative designs based on segmented co-planar waveguides [152] and EM band-gap structures [149] can provide similar capabilities using flexible materials. The interaction between the human body and signals confined on its surface can also provide the basis for sensing technologies. For example, a metamaterial textile strip can be used as a touch sensor to remotely control a smartphone by exploiting the signal drop that results from the interaction between the EM field and the finger [146]. They can also be used to improve the angular coverage in blind-spots around the body, as in Fig. 14, where multiple antennas would normally be required. A wearable waveguide could also be used by nearby wireless wearables by coupling their signals around the body with lower losses compared to radiative propagation; an example of wearable waveguides with a wireless feed is shown in Fig. 13(d).

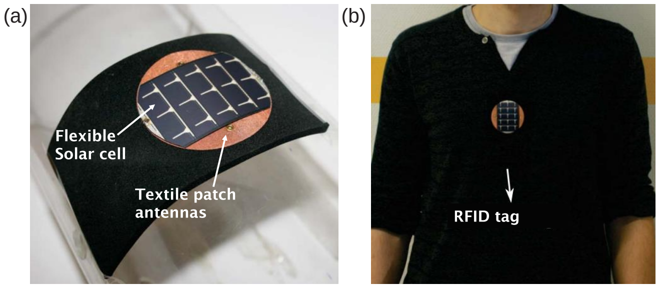

FIGURE 15. **A textile antenna acting as (a) a modular RFID platform with integrated flexible solar energy harvesting and its integration in clothing (b) [155] (© IEEE 2016).**

Wearable metamaterials have demonstrated many attractive capabilities for sensor networking, but further work is necessary before their widespread use becomes possible. First, the washability of the textiles needs to be addressed, as discussed in Section V B. Secondly, the electrical and mechanical performance of the metamaterials needs to be further improved. A key limitation is that existing conductive textiles require a trade-off between their conductivity and flexibility or stretchability. Emerging materials for e-textiles, e.g. liquid metals, have shown potential for achieving an RF performance close to conventional copper-based devices while retaining flexibility and reliability [147].

IV. Integration Platforms

We define the integration platforms of wearable devices as technologies and fabrication processes. We first review two platforms for realizing passive components: (Section IV-A) textile antennas and (Section IV-B) additively manufactured components, as well as two active semiconductor fabrication processes: (Section IV-C) fully-integrated CMOS systems, and (Section IV-D) novel large-area semiconductors. The hybrid integration of different fabrication and packaging processes is finally discussed (Section IV-E).

A. Wearable Antennas as a Platform for Communication, Energy Harvesting, and Sensing

Wearable and textile antennas show great potential in beyond-5G networks [156] and will play a key role to enable a wide variety of emerging human-centric 6G services [157]. This is especially true when these are part of textile wearable wireless nodes [158], with on-board active electronics [159] interconnected by passive textile microwave components [160], and whose battery autonomy has been augmented by energy harvesters [161]. Such reliable and pervasive integration of multiple wearable components and modules on a wearable antenna platform requires a holistic design paradigm [129] as depicted in Fig. 3. Relying on dedicated manufacturing processes and variability analysis [162] to jointly optimize the wireless communication, sensing, computing, actuating, energy harvesting, and power-management subsystems as integral parts of a high-performance, energy-efficient wearable systems. Only then, the complex set of multi-disciplinary, and often conflicting, design requirements imposed on next-generation smart wearables can be fulfilled. These, in turn, may be part of a bio-wireless network [163], integrating biosensors and wireless communication, localization, tracking and sensing technologies within an ambient assisted living platform.

Prior to wearable component and system design, the pertinent fabrics' or foams' complex permittivity and the conductors' (e-textile, printed silver, flexible conductors) effective conductivity must be characterized. Different techniques have been proposed. [164] compares measured and simulated antenna impedance and radiation efficiency data, while [165] exploits a ridge gap waveguide. Material-selection is critical for the stable, energy-efficient operation of the system to be designed. Although flexibility is typically required for user comfort, sufficient mechanical stability is needed to safeguard system reliability and performance. While materials readily found in the application of interest are particularly suited in terms of cost and unobtrusiveness of the design, among others, drapable materials are to be avoided and the compression factor of substrates should be limited to 30% to avoid excessive shifts in the resonant frequency. Moreover, to ensure stable operation in different environmental conditions, materials with low moisture regain [164] should be preferred. Water-repellent foams and breathable textiles with high air content improve antennas' efficiency owing to their ϵ_r being close to that of free space.

The development of wearable systems with high autonomy starts with an energy-efficient design, based on a dedicated antenna topology that provides excellent antenna-platform isolation to avoid parasitic coupling of antenna radiation with the human body and nearby electronic circuits. The latter enables the compact integration of electronic circuitry on the wearable antenna to improve reliability by avoiding fragile connections, enhance electromagnetic compatibility (EMC), and achieve better energy efficiency through pervasive full-wave/circuit co-optimization [129]. Moreover, multiple energy harvesters [161] may directly be positioned on the antenna platform, providing a continuous flow of energy in different operating conditions. An example of a modular RFID sensing system implemented over a textile antenna is shown in Fig. 15, where the flexible solar cell shares the area of the antenna's radiator for improved integration.

Besides collecting solar, thermal, or kinetic energy [161], wearable rectennas [29] may be deployed, even in flexible wristbands [45], either to scavenge ambient RF power originating, for example, from 0.5 W two-way talk radios [22], or from intentional RF power transfer [174]. Exploiting broadband rectenna arrays, potentially screen printed on a cotton tee-shirt [48], may also yield a larger harvested RF power [175]. Wearable microwave and mmWave sensing systems, reviewed in Section C, are particularly useful in wearable wireless health-monitoring systems [176]. For this purpose, wearable RFID tags [155], [177], [24] with on-board harvesting, sensing, processing, and decision-taking capabilities can be exploited. Also, on-body active textile

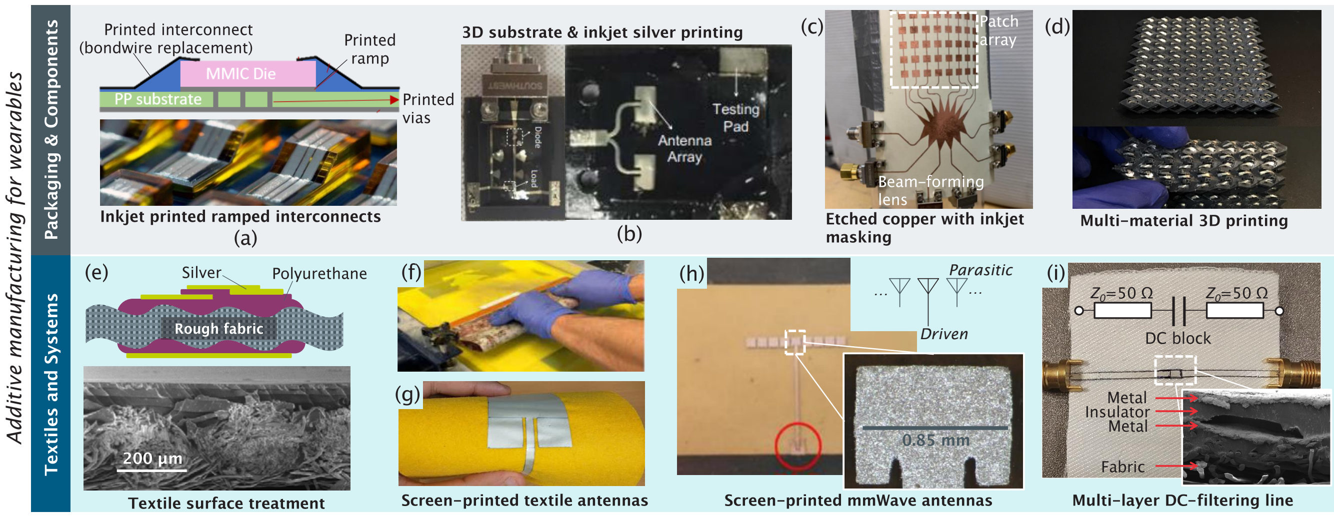

FIGURE 16. Additively manufactured microwave components for packaging and wearable applications: (a) ramped interconnects [166] (© IEEE 2022); (b) energy harvesting system-in-flexible-package [167] (© IEEE 2019); (c) flexible Rotman lens [168]; (d) re-configurable FSS [169]; (e) direct printing on textiles, diagram, and SEM micrograph [170] (© IEEE 2014); (f) screen-printing [171] of (g) robust antennas [172]; (h) 77 GHz printed wearable array [173]; (i) highest-frequency printed textile transmission line: 50 GHz DC-blocking line [21].

antennas themselves may, for example, monitor exposure to incident RF fields [178]. In this respect, inkjet-printed self-sintering epidermal antennas [179] may be leveraged to directly deploy the wearable system on the skin.

B. Additively-Manufactured Flexible Devices

From printed packaging to printed large-area circuits, additive manufacturing techniques can be used to realize microwave systems. Additive manufacturing techniques such as 3D printing, inkjet, screen, and dispenser printing have enabled the implementation of novel customized designs onto flexible substrates. These techniques come with low cost and less material waste compared to conventional subtractive manufacturing, i.e. photolithography.

1) mmWave Packaging and Interconnects

With 5G technologies rapidly transitioning to mmWave frequency band, the influence from interconnects between RF components in a packaged device become more prominent. Traditional ribbon or wire bonds introduce higher parasitic loss, while additively manufactured interconnects can offer superior RF performance, with a more rugged, planar, and conformal structure. Inkjet printed ramp interconnects have been proposed utilizing SU8 dielectric ink [180], [181]. The fabrication process and insertion loss of ramp interconnects were characterized using microstrip line structure. Each interconnect consists of a 75 µm wide and 300 µm long line inkjet printed with silver nano particle ink onto the ramp. The measured S_{21} showed that less than 0.5 dB is added from each interconnect when compared with reference lines. This structure can be easily integrated with mmWave components in die packages, as shown in Fig. 16(a), with a mmWave system-in-package featuring ramped interconnects shown in Fig. 16(b).

In addition, it has also been reported that additively manufactured "smart" packaging can achieve highly integrated flexible modules, as shown in Fig. 16(b). This design realized 3D integration by utilizing non-planar interconnects with various heights to connect different parts of the circuits. The package includes inkjet printed on-package antenna covering 5G mm-wave band from 24.4 to 30.1 GHz, and an embedded energy harvester to replace external batteries. The demonstration of this full system in a compact flexible package provides the possibility of integrating wearable devices, presenting an improvement over rigid ICs and packages.

2) Additive Manufacturing on Flexible Substrates

Taking advantages of additive manufacturing techniques such as 3D printing, more flexible materials become available for electronics design, such as PLA from FDM printing and Flexible 80A (Formlabs) from SLA printing. However, when integrating 3D printed polymers into RF components, one of the crucial requirements is to have low RF loss and low surface roughness. Polypropylene has been proved to have low loss tangent of 0.001 with good surface wetting for inkjet printing, which are suitable for 5G mmWave applications. Wearable antennas can be inkjet printed onto these flexible materials with silver nanoparticle ink.

Apart from 3D printed flexible materials, additive manufacturing also supports flexible Rogers Corp. substrates, Kapton polyimide, Liquid Crystal Polymer (LCP), and Teflon/PTFE substrates, combining functional printed silver nanoparticles (SNP) and polymer-based inks with photolithography of copper laminates. Fig.16(c) shows a flexible, high-gain and wide-angular-coverage mm-wave Rotman-lens-based antenna array fabricated using inkjet photoresist masking on LCP substrate [168]. The array achieves a high (17 dBi) measured gain with an angular

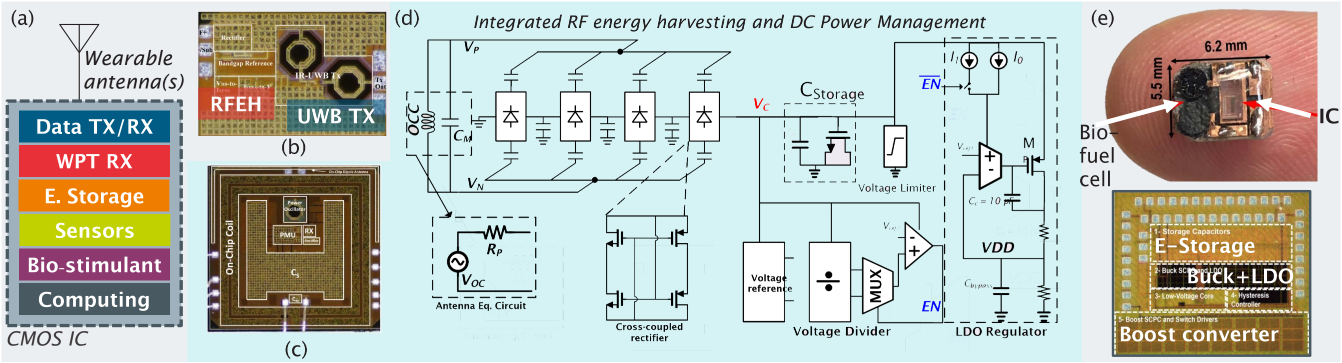

FIGURE 17. **Fully-integrated CMOS systems in body-centric power-autonomous applications: (a) high-level conceptual block diagram of the components reported in CMOS integration; (b) micrograph of an RF-powered UWB transceiver for vital signs monitoring [24] (© IEEE 2020); (c) micrograph of a power harvesting system for implantable neural interfaces [182] (© IEEE 2021); (d) schematic of an on-chip harvester [182] (© IEEE 2021); (e) a wearable bio-fuel cell-powered energy harvesting IC [183] (© IEEE 2021).**

coverage around 110°, that does not deteriorate by wrapping or folding the structure.

Printed components can also enable reconfigurable devices. Traditional reconfigurable wireless devices generally utilize active components such as PIN diodes, switches, and varactors to tune the performance on-the-fly. While active components can achieve fast response, at the same time, they can be expensive, fragile, and require a complex feeding network that increases the size and cost dramatically. With additive manufacturing processes, reconfigurable wireless devices can be realized on a flexible printed substrate with shape-changing capabilities to tune the performance mechanically, showing unprecedented tunability and deployability.

One of the first demonstrations of mechanically reconfigurable Frequency-Selective Surface (FSS) at mm-wave frequencies is shown in Fig. 16(d). The resonant frequency of this FSS can be tuned from 22.4 to 26.1 GHz by changing the folding angle by 50°. Enabled by the flexible 3D printable resin, this FSS was designed as "mirror-stacked" multi-layer configuration that doubles the conductor density without increasing the size. As a result, the measured prototype shows up to 12 dB lower insertion loss compared to a single layer counterpart [169]. The novel origami-inspired multi-layer design along with high-resolution hybrid printing process makes it an ideal easy-to-scale candidate to use in mmWave applications.

3) Direct Printing on Textiles

While printing high-performance microwave systems has been demonstrated, directly printing RF circuits on textiles for wearable applications poses a unique set of challenges. The roughness of fabrics, clearly seen in the scanning electron microscope (SEM) micrograph in Fig. 16(e), implies that many layers of conductive ink (often silver) will be required, making the cost prohibitively high. The use of screen-printable interface layers was proposed to smooth out rough fabrics to enable components such as antennas to be inkjet printed [170]. Nevertheless, this approach is limited to relatively homogeneous fabrics, and is not compatible with non-woven textiles such as felt [45], widely used as a wearable antenna substrate [45], [38], [51].

An alternative transfer printing process relies on a heat-pressed adhesive. The circuit's traces are printed on the smooth interface film, typically polyurethane (PU), before being heat-pressed onto virtually any textile substrate as in Fig. 16(f) and (g) [172], [171], [21]. A screen-printed silver 2.4 GHz patch antenna heat-pressed onto felt was characterized before and after 10,000 bending cycles, showing an unchanged S_{11} and far-field response [172]. Such a fabric-independent fabrication method could be combined with textile-independent broadband antenna designs [50] for rapid re-design and adaptation of RF circuits for integration in different garments.

Until recently, passives directly printed on textiles were only demonstrated for sub-6 GHz applications, namely up to 2.4 GHz [172], [171], [170]. However, a multi-layered novel microstrip line was recently demonstrated operating as a high-isolation and high-power-handling DC block on two textile substrate, felt and polyester cotton, up to 50 GHz [21]. The integration of the lossy heat-pressed capacitor within the microstrip line, as shown in Fig. 16(i), yielded a high-performance DC-block, with comparable attenuation to inkjet and spray-coated lines on smooth polymers. Therefore, [21] demonstrates that the unfriendliness of most fabrics from a printing perspective does not hinder the realization of high-performance mmWave passives. Such all-printed structures improve the immunity to failure over cycling bending, where discrete capacitor would typically fail [21].

C. Fully-Integrated CMOS Devices and Systems

Thanks to the high integration capability of semiconductor technology, fully integrated systems on commercial CMOS technologies are emerging as a promising solution for future wearable, biomedical, and even implantable systems. Fig. 17 shows an overview of CMOS-enabled wearable devices and their potential applications in mm-scale nodes [182]. The main enabling pillars of the next-generation miniaturized wearable and implantable systems are sustainable power delivery, low-power connectivity, efficient processing algorithms, and ubiquitous sensing. As illustrated in Fig. 17(a) these functionalities can be integrated on the same IC, either with off-chip wearable antennas, or with fully-integrated on-chip coils or antennas. Recent integration efforst included the integration of a highly-sensitive RF energy harvesting front-end with a low-power Ultra-Wideband (UWB) transceiver, enabling the tag to have a read-range of 51 m using compact antennas [24]; the die's micrograph is shown in Fig. 17(b).

Despite the undeniable advantages of mm-scale sensors [182], [184], [185], miniaturization introduces a new set of challenges for realizing the pillars of future wearables/implantable systems. The available power budget scales with the form factor and necessitates extensive power reduction techniques. Fig. 17(c) and (d) show the integration of an implantable WPT front-end including energy storage and management for neural interfaces [182]. However, due to the limited energy storage density of on-chip charge accumulation components such as capacitors, the stored energy within a small form factor becomes excessively difficult. Data communication also faces serious challenges as the overall size of the system reduces. Electrically small antennas show poor radiation efficiency at lower frequencies and tend to be operated at the GHz frequency region. However, as the frequency increases, the propagation path loss increases causing the communication to have a short range of operation.

As discussed earlier in Section B, batteries are no longer considered an effective solution for mm-sized systems. Various energy sources such as thermoelectric, light, vibration, and inductive/radiation EM-based energy transfer have been considered for this purpose [186]. Aside from the physical limitations imposed by the choice of energy sources, they vary considerably in terms of the available energy density. For instance, thermoelectric energy sources are bound to 60 $\mu W/cm^3$ and cannot be utilized for power-demanding biomedical applications such as cardiac pacemakers or neural interfaces. WPT is one of the attractive choices for fully integrated systems due to the relatively high available power density, the ability of RF fields to penetrate through bone tissues, and the feasibility of on-chip implementation of the power receiving coil. However, fully-integrated CMOS systems with on-chip antennas are inherently area-constrained. As the size of the power receiver shrinks to mm-scale, it is desired to increase the power transmission frequency to increase the rate of magnetic flux change on the receiving side and compensate for the small aperture of the power receiver, or to improve the collection area of a rectenna [184], [17]. However, the intervening biological tissues in the wireless link also have a frequency-dependent behavior toward EM waves and absorb more energy from incident EM waves as the frequency increases.

CMOS integration of wearable devices offers many additional benefits. More complex modulators, e.g. for digital backscattering, can be integrated in a very small die area, as shown in Fig. 7(c). Moreover, low-power RF rectifiers with record 1-3 V sensitivities under −20 dBm have been widely demonstrated in sub-1 GHz applications using antenna-rectifier co-design with integrated rectifiers [187], [24], [188]. Such devices could enable a generation of long-range RF-powered wearables. Moreover, several ultra-low-power computing systems with sub-threshold operation have been reported [189], enabling wearables to operate from the low DC output of far-field WPT. Moreover, miniaturized energy harvesters using smart materials can be integrated with on-chip power management circuitry as shown in Fig. 17(e). While, the integration of low-power computing, sensing, RF energy harvesting, and backscattering in a wearable CMOS system with an off/on-body interface, as in Fig. 17(a), is yet to be demonstrated, it could transform the operation of existing wearable devices.

D. Solution-processed Semiconductors for Flexible and Large Area RF Systems

Organic semiconductors constitute a very attractive material class to be used in flexible RF devices, e.g. rectifiers, mainly due to their inherent mechanical properties (flexibility, bendability, stretchability, lightweight, robustness) that render them compatible with any surface [190]. Furthermore, they offer the potential to be manufactured in large areas with high-throughput inexpensive printing techniques, such as roll-to-roll. This is particularly beneficial to the manufacturing of flexible rectennas, which can be significantly simplified, as the rectifier and the antenna can be monolithically integrated on the same substrate, skipping the extra packaging and assembly steps. Lastly, organic semiconductors can be both n-type and p-type, offering thus the possibility for implementation in complementary devices, enabling large-scale integration on plastic substrates [191].

The first examples of organic rectifiers operated in the HF bands, targeting the benchmark frequency of 13.56 MHz that is commonly used in RFID NFC applications. The poor frequency performance was due to the relatively low mobilities (<0.1 cm^2/Vs), leading to high resistance values and limited cut-off frequencies and/or output power levels. Steudel *et al.* were the first to demonstrate pentacene Schottky diodes reaching 50 MHz. Their calculations predicted a maximum operating frequency in the 100s of MHz, taking into account material (mobility, relative permittivity) and geometrical (thickness, area) considerations [195]. They went on to improve the rectifier circuitry and show improved performance of pentacene diodes operating at UHF (433 MHz, 869 MHz, 915 MHz) on a plastic (polyethylene naphthalate, PEN) foil [195]. In the last years, pentacene rectifiers have dramatically improved to reach the GHz range, enabling UHF applications. The key step to this achievement was the treatment of the Au electrode surface with a fluorinated thiol-terminated self-assembled monolayer (SAM) [196]. This not

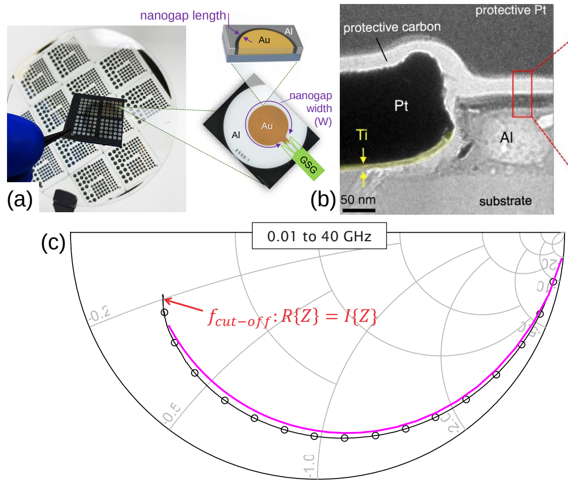

FIGURE 18. **Metal Oxide-based solution-processed Schottky diodes with record cut-off frequencies: (a) wafer-scale fabrication via adhesion lithography [192]; (b) high-resolution transmission electron microscope (TEM) micrograph on an IGZO nano-gap diode [193]; (c) measured and simulated Z_{11} of a ZnO diode showing an intrinsic cut-off frequency over 35 GHz [193], [194].**

only modified the metal/semiconductor interface to create an Ohmic contact with Au but also changed the orientation of pentacene crystals when deposited on the SAM-treated Au surface, enhancing injection and transport properties of the pentacene film, enabling $f_{\text{cut}-\text{off}} > 1$ GHz.

Transistors are also of great interest to the flexible RF community, since they are compatible with metal oxide semiconductor field effect transistor (MOSFET) fabrication process, which is still the dominant technology for logic circuit topologies. The main issue with transistors operated with the application a gate voltage is the parasitic capacitance between the gate and the source/drain electrodes. Attempts to address this issue by reducing or even eliminating the gate-to-contact overlap length, e.g., by using self-aligned lithography to obtain split-gate architectures, resulted in 20 and 10 MHz transit (unity gain) frequencies [197].

Operating in a diode-connected transistor mode, where the gate and the drain are shorted, can eliminate the effect of the parasitics due to overlapping electrodes. In this case the performance is mainly limited by the contact resistance and significant strides have been made to reduce this, e.g., by treating the metal electrodes with UV/ozone or self-assembled monolayers to reduce the Schottky barrier and increase the charge density, by applying ionic and molecular doping techniques to increase the charge carrier density of the organic semiconductor or interface engineering to enhance the charge injection [198]. Combining a contact doping strategy with ingenious patterning, Yamamura *et al.* fabricated OFETs with high frequency operation at 38 MHz that reached 78 MHz when incorporated in a rectifier circuit and operated in diode-connected transistor mode [199].

The highest performing polymer Schottky diode was demonstrated recently by Loganathan *et al.* [201], shown in

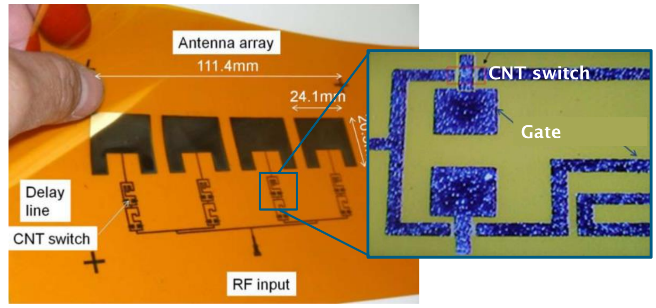

FIGURE 19. **An all-flexible inkjet-printed phased array based on a carbon nanotube (CNT) switch controlling the delay line [200] (© IEEE 2011).**

Fig. 18(a) and (b). They employed 10-15 nm long nanogap separated coplanar electrodes, fabricated with a simple low-cost technique named adhesion lithography, which has been shown to reach millimeter wave frequency response with solution-processed inorganic semiconductors (zinc oxide [193] and indium gallium zinc oxide [201]), where the measured Z_{11} from [193] is shown in Fig. 18(c). The dopant material resulted in decreasing both the resistance and the capacitance of the diode and obtaining the record extrinsic (inclusive of packaging parasitics) $f_{\text{cut}-\text{off}}$ of 3-14 GHz, and intrinsic (bare device) $f_{\text{cut}-\text{off}}$ up to 100 GHz, depending on the diode width [193]. It seems, therefore, that there is a bright future for organic Schottky diodes in the “beyond-5G” wireless communications space.

Employing advances in large-area photolithography and additive manufacturing, several examples of RF large-area all-flexible systems have been demonstrated. A flexible MoS_2-based rectenna was demonstrated operating at 2.4 and 5 GHz on a plastic film [202]. While its efficiency was limited to 50%, it demonstrates the potential of large-area RF diodes monolithically integrated with antennas. Carbon nanotube transistors were used as switches in a large-area natively-flexible phased array application, realized using inkjet printing [203], as shown in Fig. 19 [200]. With the recent advances in large-scale integration of digital circuitry on plastic substrates, where a natively-flexible microprocessor was recently demonstrated [191], an all-flexible wireless system can soon be realized.

E. Hybrid Integration in Electronic Textiles

The integration of off-the-shelf components within textiles presents challenges regarding the incorporation of rigid devices within a soft, flexible, and breathable fabric substrate/structure. Whilst conductive paths can be reliably fabricated on textiles using a variety of processes such as screen printing [204] or embroidering conductive yarns [205], the reliable attachment of components directly onto the textile will be unlikely to offer a practical solution [21]. A pragmatic approach whereby flexible filament circuits designed to facilitate the invisible integration of the electronics with the textile have been demonstrated in several works [110], [206]. Both approaches use carefully considered packaging

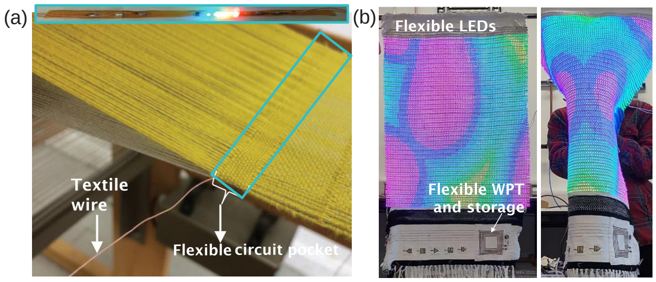

FIGURE 20. Seamless integration of electronic filaments in textiles for functional wearable and non-wearable systems: (a) MCU filament for e-textile integration and the weaving process [110]; (b) a large-area e-textile display with hybrid printed and off-the-shelf components [25].

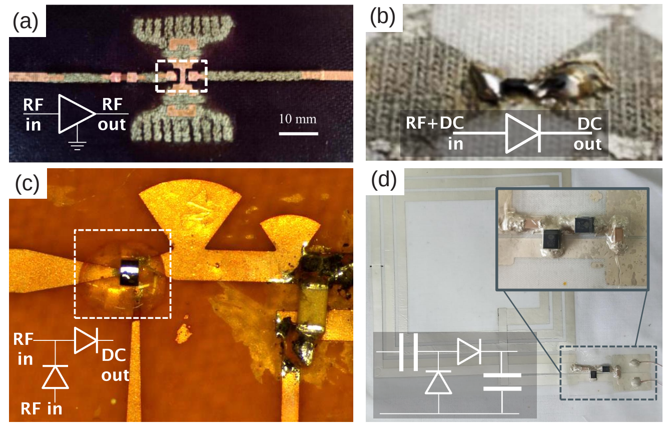

FIGURE 21. Discrete microwave components integrated in textiles: (a) packaged PA in embroidered lines [209]; (b) silver paint attachment and nail polish encapsulation of packaged diodes [48]; (c) glob-top epoxy encapsulation of bare-die GaAs diodes on copper laminate-on-fabric [29]; (d) PU-encapsulated packaged SiC diodes on printed silver-on-fabric [210].

techniques to maximize the robustness of the circuits and ensure their ability to survive the rigors of use typified by machine washing [207].

The flexible filament circuits can be woven or knitted into the fabric enabling them to be virtually undetectable by the user. Components can also be fabricated within the core of a yarn by attaching them to conductive wires and then encapsulating them to form a pod [208]. This approach is limited to components requiring two electrical connections, e.g. RFID ICs [109], or LEDs, with multiple devices being connected in series. Fig. 20(a) shows how a thin flexible circuit filament containing an MCU and several LEDs can be woven invisibly into a textile; the same fabrication method was used to realize a flexible rectenna filament integrated with a spray-coated textile-based carbon supercapacitor [49]. This technology is highly scalable as seen in Fig. 20(b), where a 32-inch display is realized using flexible LED filaments and integrated with several DC and RF components.

Fig. 21 shows examples of hybrid integration of rigid packaged devices in textile-based microwave systems. A wideband power amplifier (PA) was presented in [209] embedded in embroidered microstrip lines, showing comparable gain to the ideal simulated model and demonstrating that active e-textile components can achieve a good RF performance. While the RF and DC ground and signal paths were implemented in textiles, the bias tee was implemented using a commercial coaxial part, for testing purposes; such a bias tee could leverage the later demonstration of a DC-blocking textile microstrip [21].

Given that WPT is a key enabling technology of wearables, Fig. 21(b)-(d) show examples of rectifiers, from 6.78 MHz to 26.5 GHz, realized using hybrid integration of commercial diodes, each encapsulated using a different method. An ad-hoc water-proofing layer based on nail-polish was used to protect the packaged silicon Schottky diode, in Fig 21(b), following its attachment to a printed silver rectenna array [48]. A GaAs dual-diode bare-die can be seen in Fig. 21(c) mounted on a flexible copper trace on fabric and encapsulated using UV-cured glob-top epoxy [29], showing the highest frequency report to date of hybrid integration. The heat-pressed PU encapsulation of a 50 W textile-based 6.78 MHz rectifier, in Fig. 21(d), enables the rectifier to withstand bending without affecting its performance [210].

V. Future Roadmap for Next-Generation Wearables

The reviewed advances have paved the way for further research towards the integration of emerging microwave technologies in wearable systems. In this section, we highlight the main application domains and research areas that will see further development to enable a new generation of wearable devices to emerge.

A. Wearable Microwaves in Healthcare Applications

1) Emerging Healthcare Applications

While the use cases of wearable technologies are numerous, healthcare and biomedical sensing applications remain at the forefront of current and next-generation wearable applications. Advances in RFICs, materials, packaging, and machine learning (ML) techniques for vital sign recognition and classification have enabled many new research directions for wearables. In this section, we highlight the main application domains and research areas that will see further development to enable a new generation of wearable devices to emerge. Compared to a single modality, ML algorithms correlate multiple physiological and biochemical parameters to whole-body health or specific diseases with better accuracy. This section overviews the existing healthcare applications of microwave systems and identifies areas where new developments could accelerate the adoption of wearables in new biomedical applications.

Microwave Diagnostics and Long-Term Monitoring: for noninvasive microwave interrogation via wearables, applications with impedance, capacitive, and permittivity sensing on physical parameters such as skin impedance, heartbeats, pulses, and blood pressures; and biochemical parameters such as hydration and glucose levels, have been

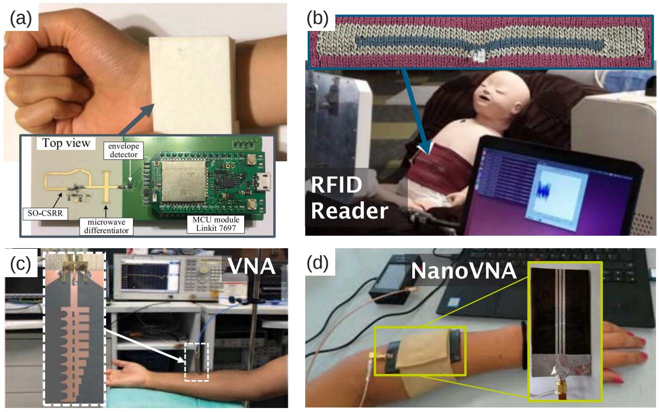

FIGURE 22. **Biomedical sensing systems using RF readers and sensors: (a) cuff-less blood pressure monitoring based on a self-injection-locked sensor [132] (© IEEE 2020); (b) wearable breathing sensor using a textile UHF RFID antenna [211] (© IEEE 2016); (c) non-invasive glucose measurements using a directional antenna and a VNA [212] (© IEEE 2021); (d) skin hydration measurement using an open-ended line and a portable inexpensive VNA [213] (© IEEE 2022).**

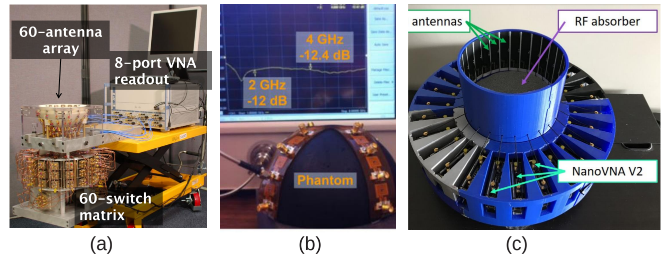

FIGURE 23. **Towards a wearable microwave breast cancer imaging system: (a) a "MARIA" switched system used in clinical trials leveraging a multi-port VNA [223]; (b) a flexible UWB antenna array validated using phantoms [225] (© IEEE 2015); a portable scanning system (not yet tested) [224] (© IEEE 2021).**

demonstrated. It is clear that the accuracy and robustness in practical scenarios will determine their clinical uses.

Many microwave sensors have been reported for breathing detection based on wearable antennas and RFID tags [214], [119], [215], [216] using a variety of EM [214], [128], thermal [119], and mechanical [215], [216] sensing approaches. Future research could see improved integration of such RF sensors with dedicated read-out circuitry for an improved read-range and for more detailed comparisons to existing clinical-grade sensors. Moreover, privacy-preserving methods will also need to be developed to prevent eavesdropping on personal data.

Other bio-parameters such as blood pressure and blood glucose levels have been addressed using an array of implementations from SILO [132] to reflectometry using a lab-based Vector Network Analyzer (VNA) [212], in Fig. 22(a) and (c), respectively. The portability and repeatability of such measurement setups is crucial for enabling long-term evaluation as well as clinical trials. The challenges around reliability and user-friendliness (discussed in the next section) will also need to be addressed to enable the circuits to withstand the harsh tests in a clinical setting prior to wide-scale adoption.

Wearable microfluidic bio-sensing represents another area for interdisciplinary microwave-enabled healthcare. On-body diagnostic using microfluidic has recently been explored in biomedical applications [217]. With extensive research on microwave microfluidic sensors including flexible and printable devices [218], [219], future wearable microfluidic systems could leverage microwave sensing technologies. However, this will depend on the availability of sensitive sampling circuitry in a small form-factor; recent advances such as single-chip VNAs [220] could enable highly miniaturized wearable microwave to sub-THz sensors [221].

Diagnosing breast cancer is another area where microwave imaging has been widely used in a clinical setting [222]. Fig. 23(a) shows a system that underwent clinical trials in 2011 [223], and was consequently commercialized by Micrima Ltd. However, the use of a complex switched antenna array and a multi-port VNA make such approaches too complex for wearable applications. Future research could integrate low-cost and highly-integrated imaging circuitry with wearable antennas (i.e. hybrid integration) for on-going breast cancer-imaging of healthy subjects; a portable system was recently proposed based on a sub-$200 compact nanoVNA, and is shown in Fig. 22(c) [224]. However, [224] is yet to be characterized.

Microwave-enabled implants: In some applications that the quality of the acquired signals is very important, "wearables" can be extended to and/or augmented by implantable devices. Next-generation applications of implantable devices such as Brain-Machine-interfaces require non-invasive biological signal acquisition with a high data rate and a high spatial resolution. Hence, there have been continuous efforts for miniaturization of the wearables/implantable systems since it leads to a higher sensor density, ease of encapsulation and implantation process, improvement of the Spatio-temporal resolution, and minimal tissue damages [226], [227].

Next-generation healthcare applications of body-centric microwave technologies extend to implantable devices such as Brain-Machine-Interfaces. These require non-invasive biological signal acquisition with a high data rate and a high spatial resolution. Hence, there have been continuous efforts for miniaturization of the wearables/implantable systems since it leads to a higher sensor density, ease of encapsulation and implantation process, improvement of the Spatio-temporal resolution, and minimal tissue damages [182]. Fig. 24 shows a conceptual vision of a closed-loop neural interface that is realized by a scattered network of mm-size nodes [182].

Microwave therapeutics: Moving from microwave-enabled wearable healthcare diagnostics to wearable therapeutics is another emerging research direction. For instance, microwave hyperthermia is a well-established technique for

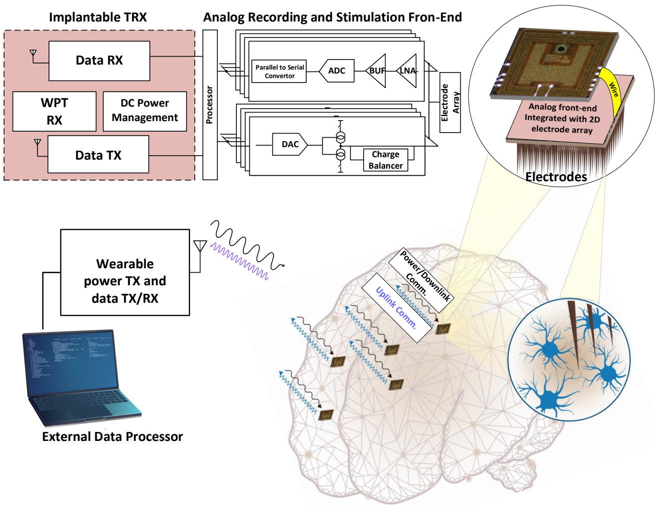

FIGURE 24. Conceptual view of a closed-loop neural recording and stimulation system for next-generation neural prostheses [182] (© IEEE 2021).

cancer treatment [228]. Nevertheless, only limited studies have explored the potential of using wearable textile antennas for hyperthermia on a simple breast-shaped phantom [229].

Therapeutic wearables face similar challenges to diagnostics. For neurostimulation and hyperthermia wearables, treatment efficacy evaluation and feedback mechanisms currently depend on the assessment by trained professionals. The outcomes can be unpredictable due to field and power distributions over a wide variety of body and tissue types. Research methodologies for such studies are typically difficult as it is challenging to create controlled experiments in human bodies, or realistic phantoms mimicking multifarious physical and biochemical parameters. Simulation tools are also limited in representing complex situations of bodies. This bottleneck calls for comprehensive multi-physics models of tissues, organs, and bodies with dynamic parameters that match well with both anatomic and molecular details. Increasing signal frequency in applications intrinsically enhances spatial and spectral resolutions and potentially enables field interaction with biomolecules for sensing. The RF issues of power attention, interference, noises, and body artifacts continue to be great challenges.

2) Safety Considerations

Needless to say, wearable microwave applications (for healthcare and beyond) must adhere to safety regulations. First published in 1982 and most recently revised in 2019, the IEEE C95.1 standard regulates human exposure to RF EM fields, from 0 Hz to 300 GHz; the FCC limits the SAR to 1.6 W/kg in consumer applications (outside a controlled environment). EM radiation in this spectrum is however non-ionizing and as a result, the harms are typically limited to reversible heating, an effect which could be noticed in high-power applications such as microwave power beaming [59].

On the other hand, given the large projected scale of wearables that could operate in multiple frequency bands and include different microwave-enabled functionalities including WPT, sensing/imaging, and communication, further research is required to assess their *long-term* safety. To explain, many studies have reported negative effects on the brain, e.g. headaches and fatigue, upon prolonged exposure to microwaves [230]. Notably, some works have reported an improvement in people's cognitive ability when exposed to 915 MHz emissions emulating those of a mobile phone [231]. While such data was mostly qualitative and difficult to reproduce [230], it shows that more work is needed to fully assess the safety of increased exposure to microwave radiation due to wearables. Flexible and e-textile wearable passive devices, such as textile-based Frequency Selective Surfaces (FSS) and absorbers [232], could also find applications in selective shielding applications to improve the user's safety in environments where exposure to high microwave power densities is anticipated, and to control or limit interference and potential health risks from co-located wearables.

Whilst, as we have discussed, it is possible to provide sensible power levels wirelessly to wearables and stay below the IEEE recommended SAR limits, it is also important that for power delivery at frequencies below 10 MHz, the limits on E-fields inside the body (i.e. the basic restrictions), as set by ICNIRP, is observed [233]. This is to ensure that unwanted nerve and muscle stimulation is avoided. In addition, compatibility with implanted devices such as pacemakers should be taken into account. Current regulations on such compatibility are given in [234].

Finally, high-power wearable applications, such as wireless power supplies, not only need to be human-compatible in terms of SAR and E-field limits: they also need to be safe in the presence of other "foreign" objects, which could be subjected to inductive heating, such as coins, foiled paper (e.g. cigarette wrapper) etc. Operating at MHz and above will tend to prevent heating into large metallic objects, but may increase the possibility of heating in thin foils. As a consequence, accurate foreign object detection is of high importance to ensure safety when utilizing a system. Various techniques have been proposed to detect foreign objects, including power balance measurements (i.e. efficiency) [236], field distribution measurements [237] and estimating measuring reflected load changes from voltage measurements in the transmit circuit [238]. None of these methods alone are likely to provide sufficient foreign object detection accuracy, and more work is required on fusion of different signals, and new methods to improve detection reliability at a sensible price point for wearable devices.

B. *Robustness and Reliability*

While efforts to tackle the integration, manufacturing, and sustainability challenges of RF/microwave components for wearable applications continue to advance, the long-term reliability of these devices and their materials remains uncertain. RF wearable prototypes in literature generally give good

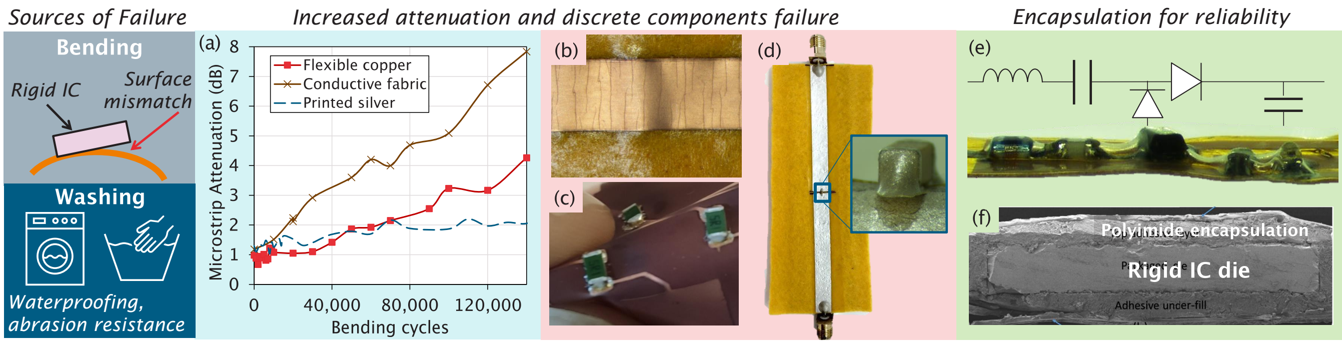

FIGURE 25. Reliability, sources of failure, their implications, and their mitigation, in flexible and e-textile wearables: (a) attenuation increase in e-textile microstrip lines with cyclic bending [235]; (b) micro-cracks along a flexible copper microstrip line after 140,000 bends; (c) a detached discrete capacitor after 10,000 bending cycles; (d) delamination of SMD components on a flexible PCB [21]; (e) encapsulation of an RF rectifier circuit using vacuum polymer [49]; (f) SEM of an encapsulated rigid IC [207] (© IEEE 2019).

performances (such as low insertion losses) when operated under controlled lab conditions [172], [239]. However, the wearable landscape presents new dynamic mechanical and environmental stresses that impose a time-dependent decay on the reliability of these microwave components.

The rate and extent to which these stresses impact the lifetime and performance of integrated microwave components, especially on very compliant substrates such as textiles, has not been thoroughly researched, and is hence, not yet fully understood. Current studies have only cursorily examined the effect of limited bending and washing stress cycles on printed antennas [172], [240], [48], screen-printed microstrip lines [21], and flexible (non-textile) inkjet-printed microstrip lines [239]. These studies report minimal differences in the RF performances of pristine devices and repeatedly bent devices over a few hundred bending cycles. Reliability trials have also extended to cover the effect of sweating [241] and dip-washing [21], indicating that textile-based microwave devices become very lossy under water absorption due to the porosity of the textile substrate [242], [243]. For example, the efficiency of a textile patch antenna, fabricated using conductive fabric, was found to decrease from 33.8% to 24% over 6 washing cycles, with the response varying based on the used conductor [242]. Reliability should also extend to the ambient operation conditions, the influence of relative humidity on the response of microstrip patch antennas has been extensively studied [244], where over 200 MHz resonance shift was recorded for a humidity change between 20% and 90%. However, these issues could be mitigated through encapsulation [242], [121]. Although the reliability results of passive antennas and microwave components show good promise for enabling the applications highlighted in earlier sections and in Fig. 1, more data on the effect of realistic bending cycles and radii ($<$ 5mm), washing cycles and programs, and the choice of materials used in fabricating microwave devices is still required.

Some common failure modes of RF flexible and wearable circuits (and more generally those containing discrete parts) are illustrated in Fig. 25. The attenuation of a 10 cm microstrip line implemented on a standard felt fabric using screen-printed silver, conductive metalized fabrics, and flexible copper films after a cyclic bending test is shown in Fig. 25(b) [235]. The results strongly highlight the benefit of using additively manufactured or printed microwave devices over equivalent devices from conventional copper-etched flexible PCBs and coated fabrics. The increased attenuation can be further explained when the micro-cracked copper trace is observed in Fig. 25(b). A possible approach to overcome such mechanical failures is by using chipless devices [245]. The elimination of rigid ICs enables the mitigation of the surface mismatch, which causes rigid ICs to fail. More recently, similar chipless epidermal systems have been reported based on acoustic resonators [246], which could represent a future approach to integrating microwave and acoustic wearable devices.

An additional challenge arising from bending is the delamination of rigid parts such as passives or active ICs [247], which is attributed to the mismatch in the surface leading to cracked solder/adhesive joints. Fig. 25(c) and (d) show the delamination of rigid surface-mount components from flexible copper DC tracks and screen-printed microstrip lines, respectively. The unreliability of discrete parts could be overcome by moving to all-printed passives such as capacitors [21], [248] and inductors [249]. However, the low Q-factor of large-value printed inductors is still a bottleneck.

Encapsulation is another route to mechanical reliability, and consequently more sustainable microwave wearable devices. Fig. 25(e) shows a micrograph of an encapsulated voltage doubler rectifier on a flexible polyimide filament [49], illustrating that the encapsulation does not affect the form-factor of the circuit. Vacuum-formed encapsulation using organic polyimide was previously used to enable flexible e-textile UHF RFID tags to withstand over 30 machine washing cycles [109]. As shown in the SEM cross-section in Fig. 25(f), vacuum-formed polyimide fully covers the rigid IC improving its adhesion to the flexible substrate.

This review reveals that the research on the reliability of wearable RF devices and systems is still insufficient. Future work should focus on intensifying reliability trials and characterization of integrated RF systems to provide a better outlook on their long-term durability. However, for this to happen, standardization of reliability test methods for wearable applications (especially textile-based applications) must develop to homogenize testing methods amongst researchers and industry to accelerate the availability of useful and informative reliability data.

C. Sustainable Manufacturing and RF Materials

With increasing commercialisation of printed electronics and the linked expansion of wirelessly connected internet of things/everything, the development of sustainable devices is at the forefront of the agenda. Typically when discussing sustainability in the context of wearable technology most reviews consider the sustainable supply of energy for the system rather than the materials it is made from as the main [31]. This is justified by the concept of sustainable in-situ replenishing of the system energy rather than replacing batteries and hence contributed to reduced waste electrical and electronic equipment (WEEE).

However, herein, we consider sustainability from a materials perspective – are the manufacturing processes and materials more environmentally sustainable. The printing processes discussed previously are all additive forms of manufacturing (e.g. inkjet, screen, dispenser, and aerosol printing) compared with traditional electronics via PCBs or silicon microfabrication which are all subtractive processes and typically harmful to the environment. Printing reduces manufacturing waste by only depositing the materials where required, and in the case of direct-write techniques only using material when required too, further reducing waste.

As has already been established, there are a significant number of printed antennas for wearables but most are currently using inorganic conductive inks, such as silver [170] or copper [250]. These can have subsequent environmental consequences due to the nano-particulate active components of the printed inks. A significant environmental factor is the printed ink which often contains volatile organic compounds (VOC) which are required to achieve the necessary viscosity of the ink for printing, ensuring it does not dry out and cause defects during printing. However, newer materials that are more environmentally friendly, such as carbon nano-tubes [251], PEDOT:PSS [252], carbon black [253], and graphene [254] have also demonstrated working RF applications, as shown in Fig. 26. These biodegradable materials are being combined with more environmentally sustainable solvents such as water, ethylene glycol and propylene carbonate [255] across a range of printed electronics applications [256]. Nevertheless, in wearable and epidermal applications, it is crucial to evaluate the biompatbility of such materials. For instance, several reports still indicate that carbon nano-tubes have a considerable toxicity which could cause cell death [257].

FIGURE 26. Examples of "green" printed antennas: (a) CNT monopole on textile [261]; (b) carbon black patch casted on textile [253] (c) printed PEDOT:PSS monopole on PET [262] (© IEEE 2015).

Biocompatibility of is an additional benefit of using organic materials as they typically have high biocompatibility in comparison with inorganics [258]. This is closely linked with the materials chosen for the binder, printing compatible solvents and the main functional material. Medical grade silicone is often used as an encapsulation as it is non-toxic and conformable, but it is not bio-degradable [255]. Combining biodegradability with biocompatibility, bio-resorbable RF components can be applied in a range of wearable and implantable applications [259], [30]. Bioresorbable RF antennas and rectifiers have been implemented based on magnesium, which combines biodegradability with high electrical conductivity [259].

A key shortcoming for these new sustainable materials and the processes is the challenging and costly scale-up for the materials such as graphene and carbon nano-tubes, and the inferior electrical and RF performance of organic conductors such as PEDOT compared to their metal-based counterparts. In addition, the printability of these inks is often problematic when high throughput is required [260].

Future work is focused on solving these problems via improved particle or material production methods [263] or investigating additional additives to improve performance [264]. This is challenging to achieve whilst still remaining environmentally sustainable, especially with concerns over nano-particle safety [265], but is essential if these devices are to become truly ubiquitous.

D. Next Generation RFID and RF Sensing

Implantable and organ-based RFID sensors are expected to augment the sensing functionalities of wearables. In this context, wearables can act as a readout and also a multi-sensor platform which can enhance the read-out of devices such as neural interfaces, seen in Fig. 24, or RF-controlled drug delivery [266]. In this context, "RFID" will extend beyond the existing standards to fulfill the demands of the emerging wearable market. Both EM/RF sensing techniques will develop to enable:

1) Multi-chip wearable devices as edge computers, wherein the sensing and even the computational and data-storage activities are spread over several low-power battery-less nodes [267].

2) Battery-less multi-sensor devices becoming implantable, over organs, and in ingestible devices, e.g. for drug delivery [266].
3) Backcattering and low-power communication being integrated with well-established standards such as LoRaWAN [268] or Bluetooth Low Energy [269].
4) Further development and optimization of "computational RFID", where a microprocessor implements a standard-compliant backscattering protocol and encodes the "ID" with sensor data [270], towards specific wearable applications.
5) Further development in transceiver architectures for joint sensing, communication, and even SWIPT towards truly multi-functional RF front-ends [271].

These developments will require research in low-power computing, read-out and sampling circuitry of RF sensors, as well as the system-level integration to motivate a new generation of RFID-like standards that supports sensing and communication.

E. Large-Scale Integration and Active Circuits

Fully-integrated CMOS systems and application-specific ICs (ASICs) will play a major role in future wearable systems. The low-power consumption [189], ability to extract and manage power from ultra-low-output harvesters [183], and long-range and high-sensitivity RF energy harvesters [272], [24] will be major enablers of the next generation of wearables. Methods of integrating and packaging such CMOS ASICs as well as designing them specifically for interaction with large-area wearable components such as antennas, energy harvesters, sensors, and actuators will be next research steps before custom ASICs make their way to large-scale textile-based wearables.

Moving beyond CMOS and traditional semiconductors, next-generation RFID and RF energy harvesting will start to leverage the advances in large-area organic semiconductors, which have already unveiled their potential to be implemented in low-cost flexible RF rectifiers [192], [201], [193]. Looking forward, a holistic approach should be followed to tackle simultaneously the existing challenges and drive the technology push:

1) Synthesis of new materials with high purity, small number of structural defects and printing capabilities; material discovery using machine learning algorithms could be pivotal in the next years.
2) Device structure optimization via novel designs that overcome the scaling constraints and other geometrical limitations.
3) Stability towards oxygen and moisture with low-cost encapsulation methods.
4) Innovative circuit design to optimize the antenna design, matching circuits, device structure, and incorporate the rectenna with low-power ICs; this will be more likely application-driven as different end-products will have different performance demands.
5) Integration of RF large-area devices [193] with flexible high-density logic [191] towards all-flexible wireless ASICs.
6) Development of green manufacturing processes with low energetic footprint, low material waste and potential for recyclability of raw materials and device components; compliance with circularity concepts will become a sine-qua-non in future electronics industries, as discussed in Section C.

F. Towards mmWave Wearables

As with the rest of the wireless industry, wearables will have to migrate to the mmWave spectrum (>24 GHz) to benefit from the wider spectrum and the increased datarate [273]. Early works by Chahat *et al.* showed that textile antennas could meet the specifications of 60 GHz point-to-point communication [274], [275], and were followed by several textile-based or flexible mmWave wearable antennas [276]. The antenna miniaturization and high-gain promise can improve the spacial efficiency of mmWave-connected [274], [275], and even mmWave-powered [277] wearables.

Co-existence and interference of different on/off-body information and power transmission mechanisms will need to be considered [278]. In addition, the optimal split between radiative propagation [279], guided waves [280], and surface waves [153] will need to be investigated and identified. Moreover, the component-level advances in wearable mmWave components such as mm-scale textile rectennas [29] and gigabit-rate flexible backscattering modulators [83] call for further integration in mmWave wearable systems. Recent efforts have also extended beyond characterizing the effects of human proximity on propagation [279] to showing significant path loss variations depending on age and clothing [281]. The dependence of the mmWave path-loss on age not only unveils new areas for mmWave sensing wearables but also raises questions about privacy-preserving wearables in future mmWave networks.

To fully leverage the benefits of operating the mmWave spectrum, wearables integration demands a significant overhaul to existing packaging methods as well as miniaturization strategies of the associated circuitry, to reap the benefits of antenna miniaturization and higher gain. The promise of a more efficient mmWave wireless power network [168], [277] will also need to be approached with a holistic mindset to factor in the possible implications on co-existing mmWave communication and sensing systems.

G. Novel Signalling Mechanisms and Standardization

After nearly two decades of wearable and body-centric antennas and propagation research [282], future research calls for system-level novel solutions that extend beyond individual wearable antennas or transmission lines. Emerging solutions such as body-coupled low-frequency Human Body Communication (HBC) will likely see further development

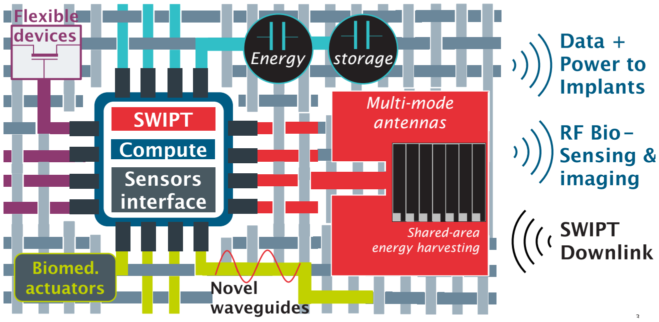

FIGURE 27. A conceptual view of next-generation e-textiles combining the reviewed enabling technologies and integration platforms.

and integration in wearable systems [283]. Moreover, further seamless integration of metamaterials with clothing [146], [67] and even with the skin [284] will enable improved connectivity in all modes of body-centric communication including communication with implants. Moreover, different frequency bands offer different advantages from lower attenuation and tissue absorption sub-100 MHz carriers [67], and improved data-rate in the microwave [146] and mmWave range [153]. Therefore, multi-band BAN applications will need to be properly defined to pave the route to standardization and commercialization.

Additive manufacturing as a rapid prototyping technology, [285], with significantly low cost for massively on-demand customization of electronic designs will speed up the development of wearable microwave passives. 3D printing technologies introduce more flexible materials that are commercially available and also low-loss for beyond-5G mmWave applications which could enable multi-layered structures. The combination of inkjet printing and 3D printing has enabled complex heterogeneous integration of flexible packages in a low-profile manner [167].

For HBC, on-body wave-guiding, and on/off-body radiation to co-exist, compelling use cases for such connected wearables and e-textiles need to be established. These use cases will likely take advantage of clothing's ability to cover a large fraction of the body, which differentiates it from existing wearable devices, and target applications in athletics, healthcare, and defense, where electronic clothing can be standardized.

H. Miniaturization and Seamless Integration

Seamless integration and ultra-miniaturization will continue to be hindered by power sources, whether that is through batteries or bulky energy harvesters. Implementing truly battery-less devices with large autonomy remains challenging and will require co-design across both the energy harvesting (including WPT) and energy consumption (communication, computing, and sensing) research fields. While steps have been made towards integrated energy harvesting, sensing, and communication as reviewed in Section C [24], there is still a need for further development for reliable integration with flexible and textile antennas. On this end, further miniaturization and realization of low-profile wearable components to enable fully invisible integration within garments is still difficult. In particular, energy-efficient wireless systems requiring an antenna with high radiation efficiency are still faced with a major challenge that is a thick and bulky antenna isolated from the body, e.g. [44], [45], or a low-profile yet unisolated antenna which suffers from tissue losses [50]. Further research on the design of wearable antennas, dielectric materials, and metamaterials will be required to overcome these problems.

Highlighted in Section V-B, the challenge of reliability manifests in miniaturized "long-life" systems. Commercial breakthrough of next-generation wearable devices requires a further improvement of the reliability of the wearable device/system and intense collaboration between a multidisciplinary team of industrial and academic partners active in textile and electronic system design and manufacturing. New methods of circuit and electronics-focused textile manufacturing will be inevitable, to enable the large-scale reliable and sustainable production of e-textiles. The adoption of novel semiconductor devices and CMOS systems will lead to improved miniaturization and can be factored in the design process of future e-textile manufacturing.

A conceptual view of a multi-function and multi-platform textile-integrated electronic system in shown in Fig. 27. Undoubtedly, power is a major challenge hindering the realization of this system. In addition to the wireless power harvesting techniques discussed previously in this review, a variety of alternative textile-based energy harvesting techniques could also be exploited to convert ambient energy in the environment [286] with the captured energy being stored within the system. Mechanical energy harvesting techniques can convert physical motion using, for example, the triboelectric effect which is the surface electrification of different dielectric materials that come into contact with, or slide against, each other [287]. Other examples include yarn-based photovoltaics that can convert incident light into electrical power [288] and thermoelectric generators that generate electrical energy from a thermal gradient across a thermoelectric material [286]. It is likely a hybrid approach with a combination of harvesting mechanisms that can adapt to a variety of environments coupled with a suitable energy storage device that enables, for example, duty-cycled operation will be required to power such next-generation e-textile systems.

VI. Summary and Conclusions

This paper presented a holistic review of how microwave (MHz to mmWave) and wireless technologies, from well-established to emerging, can enable the next generation of wearable devices. With advances spanning the full breadth of communication, power, and sensing, the following areas have been identified as broad themes of future wearable systems research:

1) A new approach for wearable antenna, transmission line, and metamaterial co-design for multi-function and application-specific BANs.
2) Holistic design of RF frontend circuitry including energy harvesting and WPT leveraging multiple WPT modes, SWIPT, backscattering, and RF sensing.
3) Integration of CMOS systems and novel flexible semiconductors in wireless wearable systems through hybrid packaging and additive interconnects.
4) Co-design of microwave healthcare diagnostic and therapeutic systems with clinical requirements and reliability considerations to enable real-world testing and evaluation.
5) Extending wearables to interact with and enable implantable devices through communication, WPT, and joint multi-parameter bio-sensing.
6) Integration of computing in wearable RFID and RF-enabled systems enabling intelligent wearables.
7) Embedding sustainability in the design process of wearables from materials choice, (additive) manufacturing, and circuit and network design for power-optimized operation.
8) Standardizing the fabrication and reliability testing processes towards commercial/wide-scale adoption.

We foresee an increase in interdisciplinary research and development activities at the interface of new materials, advanced microwave technologies, and applied circuits and wireless systems to solve the outstanding challenges and enable the emergence of a new generation of ubiquitous wearable systems.

Acknowledgement

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