

Compact, Flexible Harmonic Transponder Sensor With Multiplexed Sensing Capabilities for Rapid, Contactless Microfluidic Diagnosis

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Abstract—In this article, we design and experimentally demonstrate a flexible, low-profile harmonic transponder sensor, capable of performing multiplexed fluidic sensing. The harmonic transponder comprises multiple reconfigurable electrically small antennas (ESAs) integrated with microfluidic channels for receiving radio frequency (RF) signals at the fundamental frequencies (f_0), as well as a broadband microstrip monopole for retransmitting the second-harmonic signal ($2f_0$) to a sniffer. Such a frequency orthogonality can help suppressing possible echoes, clutters, and crosstalks in the rich-scattering environment. We show that injection of different liquid samples into a microfluidic channel, which tunes the operating frequency of an ESA, can be precisely recognized by analyzing the shift of peak second-harmonic received signal strength indicator (RSSI) in the frequency-hopping spread spectrum (FHSS). We also demonstrate the possibility of performing rapid and multiplexed noncontact detection with the proposed harmonic transponder sensor. We envision that this battery-free and lightweight multiplexing wireless sensor may benefit various Internet-of-Things (IoTs) and healthcare applications, such as rapid contactless point-of-care (POC) and drive-through tests.

Index Terms—Contactless test, electrical small antenna (ESA), electromagnetic interferences, fluidic channel, harmonic radar, harmonic sensors, metamaterial-inspired antenna, passive wireless sensors, point-of-care (POC).

I. INTRODUCTION

IN THE past decade, with the rapid development of Internet-of-Things (IoTs) and smart devices, the power-saving wireless sensing techniques have drawn rapidly growing interest because the integration of wireless communication networks with sensor nodes can provide significant advantages in terms of high data rate, real-time monitoring, and the capability to synchronously upload information for the cloud-based data analysis [1], [2]. The first generation of wireless smart sensors

can be dated back to 2000 (e.g., wireless pressure sensing [3]), and ever since then, it has been widely demonstrated in monitoring the environment parameters [4], biological parameter [5], humidity [6], and temperature [7], to name a few. However, to date, most of the wireless devices are active devices; namely, they usually need an external power source, such as a battery or an energy harvester, which inevitably adds a significant amount of complexity and error sources to the system [8]. To enhance the system's durability and robustness, and to reduce maintenance costs, many battery-free wireless sensors have been developed, which, in principle, can be divided into two categories. The first type is based on the near-field inductive/capacitive coupling mechanism, which has been demonstrated to be effective for versatile LC-based biomedical sensors [9]–[13] and capacitive pressure or humidity detectors [3], [14], [15]. However, this near-field coupling scheme has the commonly known disadvantages of short interrogation distance that is limited to several inches; this poses an inconvenience for practical sensing applications. To overcome such limitations, electromagnetic backscattering techniques have been exploited to perform long-distance wireless sensing. In this manner, microstrip antenna sensors and passive radio frequency identification (RFID) have been proposed for remotely detecting environmental changes [16]–[18]. Unfortunately, even though such systems could have longer interrogation distance, backscatter sensors are usually vulnerable to direct coupling, scattering interferences, and clutters surrounding them.

Compact, passive harmonic sensors are gaining increasing attention. Similar to a harmonic radar [19] that has been successfully used in tracking objects with a very small radar cross section (RCS) [20]–[22], a harmonic sensor launches and detects orthogonal harmonics to avoid multiple interferences, clutters, and crosstalks between T_x and R_x [23]–[25]. These harmonic sensors have been extended to remote sensing of strain and cracks [26], [27], humidity sensing [28], localization of underground buried assets [29]–[31], and noninvasive detection of critical symbols in healthcare applications [32]–[35]. Especially, facing the crisis of global aging and pandemic (e.g., COVID-19) [36], rapid, low-cost, and disposable point-of-care (POC) tests and drive-through tests are in exponentially growing demands. Recently, we have proposed a passive harmonic transponder hybridized with an antenna sensor for monitoring

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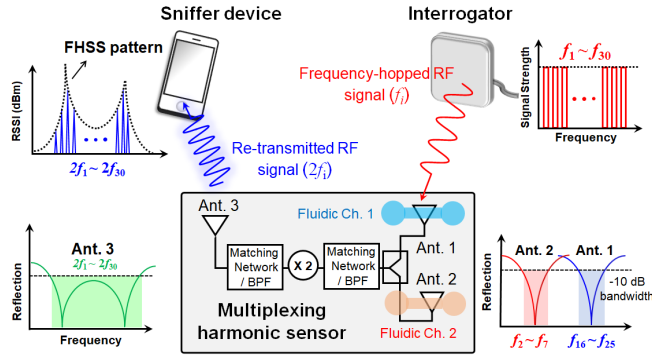


Fig. 1. Schematics of the integrated harmonic sensor based on microstrip antennas, where antennas Ant. 1 and Ant. 2 exhibit a liquid-reconfigured resonance at the fundamental frequency f_0 , and antenna Ant. 3 exhibits insensitive wideband resonance centering in the second-harmonic band $2f_0$. The full-passive harmonic sensor receives and backscatters the RF signals at orthogonal frequencies, so as to avoid clutters, multipath interferences, and crosstalks. The type of liquid droplets in each fluidic channel can be retrieved by analyzing the FHSS patterns of the recorded second harmonic signals.

liquid levels in medical and healthcare applications [37], [38]. This technique is based on the harmonic received signal strength indicator (RSSI) data under the FHSS of UHF RFID signals, which is particularly suitable for convenient POC and drive-through tests. In fact, the already popularly deployed RFID toll tag readers can be used as interrogators, and healthcare workers can use smartphones as data sniffers/decoders for drive-through tests. Such a contactless, wireless sensing platform will not only drastically improve the throughput but also reduce the risk for the healthcare workers if testing with contagious diseases. Although the existing harmonic transponder sensors have several advantages in healthcare and IoT applications, they have certain intrinsic limitations. As an example, they generally lack the ability to simultaneously cope with multiple test channels or multiple test parameters [39]–[41], which may not satisfy the complexity requirement of many healthcare applications in practice. Another limitation is the lack of good mechanical flexibility and compactness, which further limits the applications of these harmonic sensors in the fields of wearable and textile electronics. For example, harmonic-based antenna sensors in [40] and [41] were based on semirigid, dual-, or multimode microstrip patch antennas (i.e., cavities with open sidewalls), of which only a specific cavity mode is perturbed by the dielectric loading, while others remain unchanged. Considering the complicated modal profile in a compact cavity, it is rather difficult to design a multiplexing sensor.

We herein propose a lightweight and flexible multiplexing harmonic transponder sensor, which allows for rapid, *in situ* detection of at least two types of liquid samples. As sketched in Fig. 1, the system consists of a transceiver (T_x) that transmits a constant-strength frequency-hopping sequence with totally 30 channels $[f_1, f_2, \dots, f_{30}]$ to the multiplexing harmonic sensor. The frequency-hopped radio frequency (RF) signal is received by the sensor's electrical small antennas (ESAs), with strength modulated by the sample under test (SUT) in the fluidic channels. The received

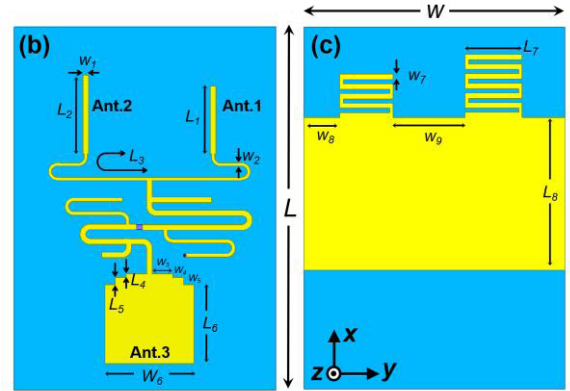
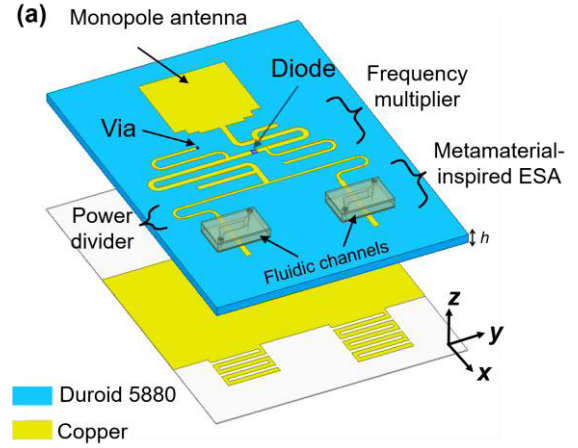


Fig. 2. Schematics and dimensions of a compact, fully passive harmonic transponder comprising two ESAs integrated with separate fluidic channels, a power divider, a frequency multiplier, and a broadband monopole antenna. (a) 3-D view, (b) top view, and (c) bottom view of this duplex harmonic sensor.

RF signals then undergoes frequency doubling (i.e., $[f_1, f_2, \dots, f_{30}] \rightarrow [2f_1, 2f_2, \dots, 2f_{30}]$) and is retransmitted to the sniffers. Finally, the dielectric property of the SUT can be retrieved by postprocessing the high-dimensional frequency-hopping spread spectrum (FHSS) pattern $[2f_1, 2f_2, \dots, 2f_{30}]$. We should emphasize that the proposed harmonic sensor can be generalized into a multiplexed sensing platform that can simultaneously monitor several SUTs, with good isolation and ignorable mutual coupling. The proposed technique may be of interest for emerging wearable, textile, and implantable electronic devices. In the following, we will discuss the design and practical implementation of this flexible, fully passive multiplexing harmonic sensor used for contactlessly sensing two binary mixtures in the far zone.

II. DESIGN AND MEASUREMENT OF HARMONIC TRANSPONDERS

Fig. 2(a) illustrates the 3-D geometry of the proposed harmonic transponder, which comprises two metamaterial-inspired ESAs [42]–[44], a power divider, a passive frequency multiplier, and a rectangular monopole antenna with their optimal design parameters as summarized in Table I. The metamaterial-inspired ESAs are typically composed of LC resonant structures that are inspired by the design of the unit

TABLE I

SUMMARY OF DIMENSIONS IN THE HARMONIC TAG (UNIT: MILLIMETERS)

Par.	L	W	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8
Value	100	70	19	22	42	1	2	22	16	43
Par.	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	
Value	1.58	0.85	5.7	3	3	25	1.5	10	20	

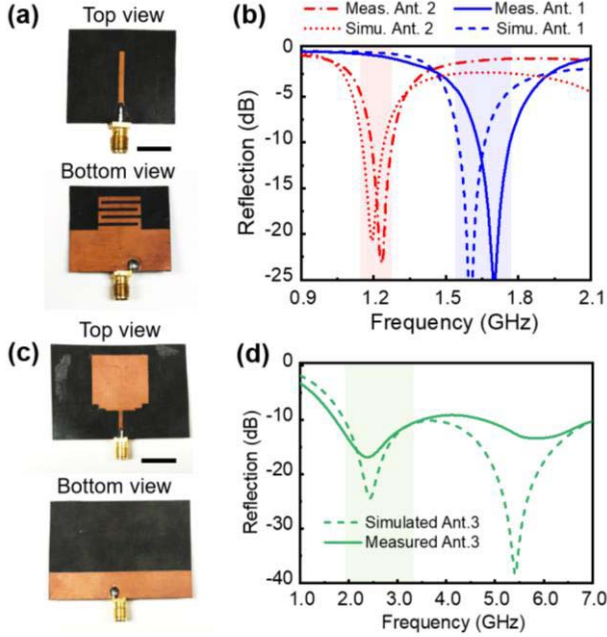


Fig. 3. (a) Photographs and (b) measured reflection coefficient for the metamaterial-inspired ESAs (Ant. 1). (c) and (d) Similar to (a) and (b), but for the wideband monopole antenna. The scale bar in (a) and (c) are 1.5 and 2 cm, respectively.

cell (or metaatom) [45]–[48] constituting the metamaterial. Therefore, when compared with metamaterial-based ESAs, the metamaterial-inspired ESAs can be more readily designed and physically implemented. Here, the metamaterial-inspired ESAs (Ant.1 and Ant. 2 in Fig. 1) used for receiving fundamental tones comprise a short stub and a grounded meander line. The inductive nature of a meander-line metaatom [42] can compensate for the capacitive nature of a short monopole, thus forming a resonant radiating system matched to a 50- Ω input impedance, without any matching components or stubs. The generated second harmonics are retransmitted by a wideband rectangular monopole antenna (Ant. 3 with a 50- Ω input impedance in Fig. 1) to the sniffer/reader. The two layers of the harmonic transponder are separated by the Rogers 5880 substrate with relative permittivity $\epsilon_r = 2.2$, loss tangent $\delta = 0.0009$, and thickness $d = 0.508$ mm. In this work, commercial software, ANSYS High Frequency Structure Simulator (HFSS), was used for simulation and optimization of the proposed antennas [49]. The Advanced Design Simulator (ADS) was used for the design of the power divider and the frequency multiplier [50]. Fig. 3 presents the photographs and the measured reflection spectra for these three antennas. The results in Fig. 3(b) show that the two narrowband ESAs resonate at 1.23 and 1.73 GHz, with a

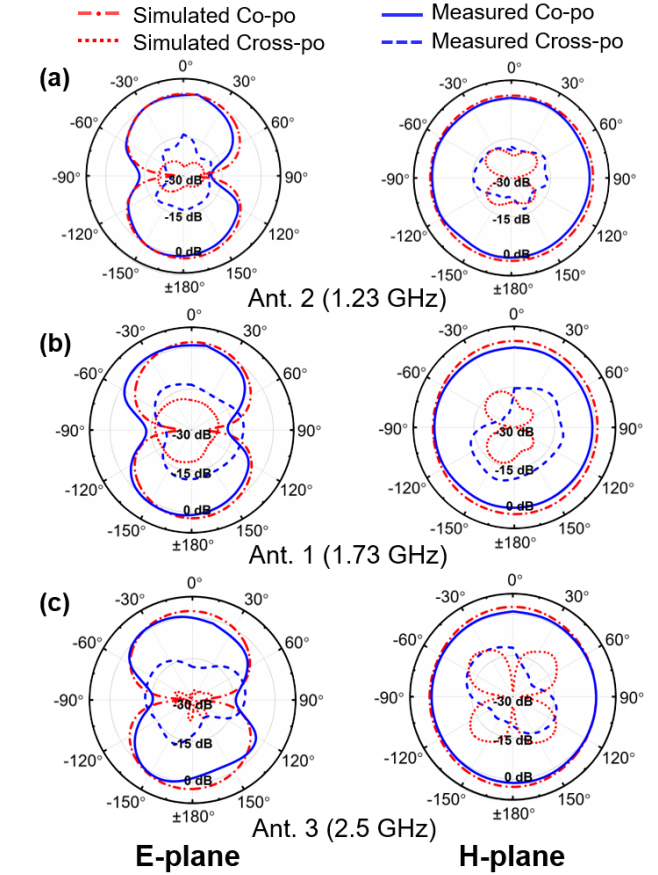


Fig. 4. Radiation patterns for (a) Ant. 2 at 1.23 GHz, (b) Ant. 1 at 1.73 GHz, and (c) Ant. 3 at 2.5 GHz.

bandwidth of 130 and 160 MHz, respectively. The rectangular microstrip monopole antenna exhibits a wideband resonance (2–6 GHz), covering the entire second-harmonic spectrum of the two ESAs, as shown in Fig. 3(d). The measurement and simulation results are in a good agreement, with the percentage frequency up-shift 6.5% for Ant. 1 and 4% for Ant. 2, due to fabrication errors and variations in the permittivity of the substrate.

Fig. 4 reports the radiation patterns on the E (x - z) and H (y - z) planes for the three antennas in Fig. 3 at the operating frequency (1.23, 1.73, and 2.5 GHz). Both the measured and simulated results show that the proposed antennas exhibit omnidirectional radiation properties with linear polarizations. The measured maximum gains for Ant. 1, Ant. 2, and Ant. 3 are 2, 1.8, and 2.1 dBi, respectively. The measurement results agree quite well with the simulated ones, as can be seen from Fig. 4. We also note that for all the three antennas, the cross-polarization patterns are lower than -15 dB on the E - and H -planes, when compared with their co-polarization patterns.

These antennas are integrated with a passive frequency multiplier [Fig. 5] and a power divider [Fig. 6] for building a passive harmonic transponder. The schematic and the photograph of the passive frequency multiplier are presented in Fig. 5(a) and (b), respectively, of which the shunt quarter-wavelength ($\lambda_0/4$) short-circuited and open-circuited

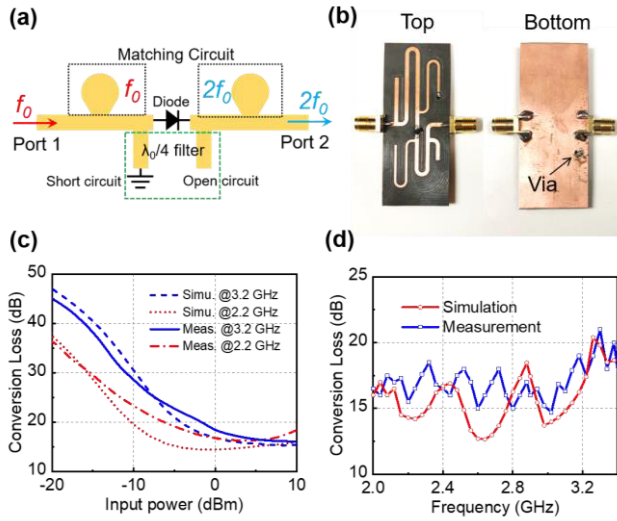


Fig. 5. (a) Circuit schematic and (b) implementation of a compact passive frequency multiplier, and its simulated and measured conversion loss in (c) as a function of input power and in (d) at different output frequencies.

stubs are placed around a Schottky diode (HSMS 2850). At f_0 ($2f_0$), the $\lambda_0/4$ short-circuited stub is an open (short) end at its input, whereas the open-circuited stub behaves like a short (open) end. Consequently, the injected RF signal at f_0 passes through the input matching network and reaches out to the diode, while the quarter-wavelength open-circuited stub (at f_0) at the output shorts the fundamental tone. Fig. 5(c) reports the measurement result for the conversion loss of the passive frequency multiplier in Fig. 5(b) at different input power levels. We find that at 0-dBm input level, the minimum conversion loss is ~ 15 dB at 2.2 GHz and is ~ 17 dB at 3.2 GHz. Fig. 5(d) reports the frequency dependence of this diode-based frequency multiplier at 0-dBm input power level, showing that within the frequency band of interest (2.0–3.4 GHz), the frequency doubling efficiency is fairly constant, with a less than 5-dB fluctuation. We note that the bandwidth and conversion loss flatness of the frequency multiplier can be improved by replacing tuning stubs with lumped-element matching networks and filters. Moreover, this work focuses mainly on demonstrating a proof-of-concept prototype and the FHSS sensing scheme. Nevertheless, by scaling the device and circuit appropriately, the concept can be applied to any frequency band of interest. Fig. 6(a) shows the photograph of the fabricated power divider, where two quarter-wavelength transformers with characteristic impedance $\sqrt{2} Z_0 = 70.7\Omega$ are in parallel to each other, to equally separate or combine RF powers. The simulated and measured S-parameters of this power divider are presented in Fig. 6(b), showing that the reflection coefficient (S_{11}) is lower than -20 dB over the frequency band 1–1.5 GHz, and the transmission coefficients (S_{21} and S_{31}) are ~ -3 dB within the same frequency range, with a good amplitude consistency ($|S_{21} - S_{31}| < 0.3$ dB).

III. MICROFLUIDICS-INTEGRATED MULTIPLEXING HARMONIC SENSOR

By loading fluidic channels on the top of the resonant ESAs in the harmonic transponder, a battery-free harmonic sensor

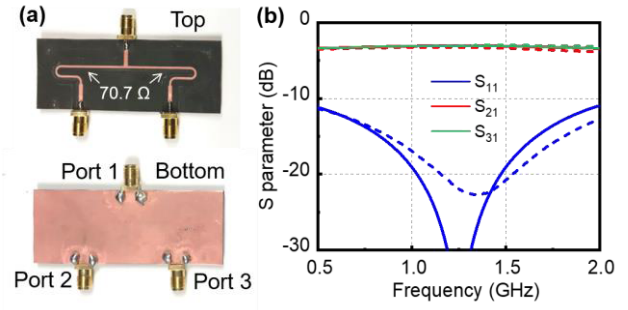


Fig. 6. (a) Top and bottom views of the fabricated power divider and (b) its simulated and measured insertion loss, return loss, and isolation. Solid and dashed lines represent the measurement and simulation results, respectively.

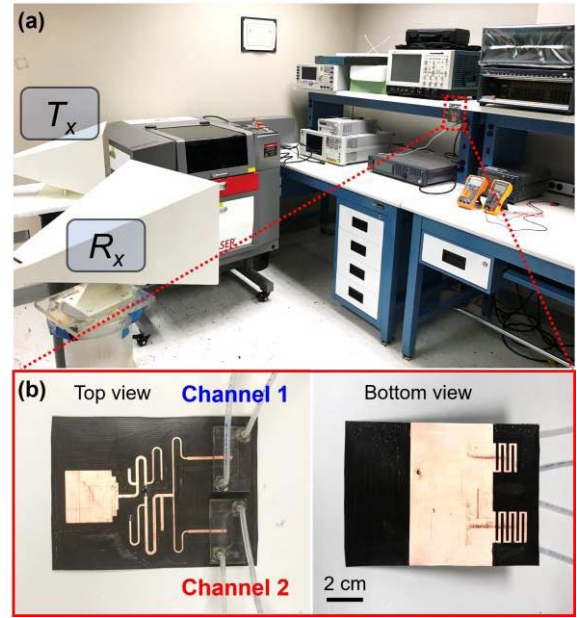


Fig. 7. (a) Bistatic measurement setup in an indoor environment. (b) Top and bottom views of the multiplexing harmonic sensor.

can be built, as schematically shown in Figs. 2 and 7. Here, we adopted the bistatic measurement configuration in a noisy indoor environment containing clutters, echoes, and interferences, as shown in Fig. 7(a). To avoid the crosstalk between the interrogator and the sniffer, the interrogator T_x was connected to a low-pass filter (DC–1.7 GHz) [51] and the sniffer R_x was connected to a bandpass filter (1.9–4.7 GHz) [52]. Fig. 7(b) presents the photograph of this multiplexing harmonic sensor, where plastic tubes are connected to the isolated fluidic channels to guide SUTs in and out. We prepared a binary mixture composed of acetone and water with different volume ratios: $A/W = 100\%$, 66% , 33% , and 0% {which gives an (real-part) effective relative permittivity $\epsilon_r = 20.7, 32, 58$, and 80 [53]}. In our measurements [Fig. 7(a)], the interrogator transmits a frequency-hopped RF signal to the harmonic sensor. The transmitter in the interrogator hops the carrier frequency every 2 s and totally 30 frequency channels are swept, with a resolution of 8 MHz. In practice, the frequency hopping rate could be several hundreds of hops per second. Synchronization

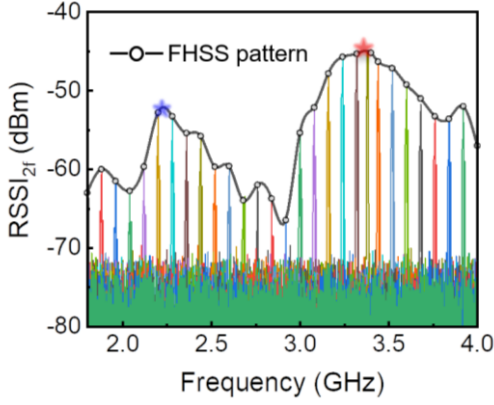


Fig. 8. Measured second-harmonic RSSI array of the multiplexing harmonic sensor in Fig. 7. The envelope of the RSSI array represents the FHSS pattern, which can be exploited to retrieve liquid properties in each fluidic channel. The licensed tones (e.g., 2.4-GHz WiFi router) in the ambient environment were excluded from the hopped carrier frequencies. Besides, those stationary and flickering peaks can be easily subtracted from the measured FHSS pattern.

between the interrogator and the sniffer is controlled by the LabVIEW program. Afterward, the nonlinear sensor doubles the frequency of the RF signal and resends the second harmonic to the R_x antenna or sniffer. The backscattered second-harmonic RSSIs measured by the sniffer form a unique FHSS pattern [see Fig. 8], whose peak frequency may be interrelated with the effective relative permittivity of the injected SUTs. The second-harmonic RSSI can be estimated using the Friis transmission equation [54]

$$\frac{P_r}{P_t} = \left(\frac{\lambda_0}{4\pi R_1} \right)^2 \times \left(\frac{\lambda_0/2}{4\pi R_2} \right)^2 \times \frac{G_r G_t G_R G_T}{L_{sys}} \quad (1)$$

where G_r is the realized gain of the ESAs at f_0 , G_t is the realized gain of the broadband monopole antenna at $2f_0$, G_T (G_R) denotes the realized gain of T_x (R_x), R_1 (R_2) is the distance between T_x (R_x) and the sensor, and L_{sys} is the system loss that includes the conversion loss of the frequency doubler [Fig. 5(c)], and dielectric/conduction losses in passive circuits and SUTs. Here, the important parameters for our measurement setup are as follows: $P_t = 25$ dBm, $R_1 = R_2 = 1$ m, $G_T = 10.5$ dBi at 1.4 GHz, and $G_R = 16.5$ dBi at 2.8 GHz. Under a fixed transmitted power P_t , the received power P_r is sensitively responsible for changes in G_r (which could be caused by the variations in dielectric properties of the liquid solution filled in the fluid channels). According to the cavity perturbation theory [55], [56], the resonance frequency shift in response to the dielectric perturbations is proportional to the electric field strength of the perturbed mode. Since the fluidic channel is placed on the top of the microstrip feedline of the ESA where electric fields are strongly localized, any small increment in the dielectric constant of SUTs may greatly downshift the resonant frequency of the ESA [53], which, in turn, results in a visible downshift in the recorded FHSS pattern.

Fig. 9 presents the FHSS patterns measured at different interrogation distances in the indoor environment shown in Fig. 7; here, except for the sensor-to-sniffer distance (R_2),

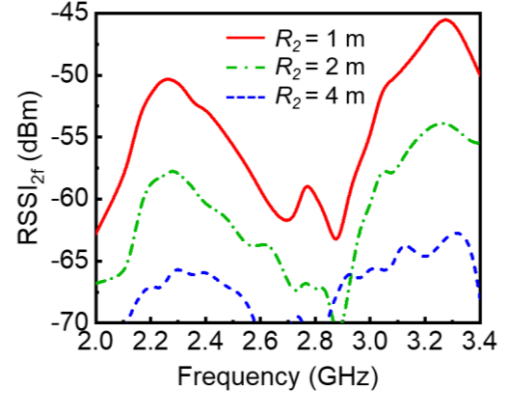


Fig. 9. FHSS pattern of the multiplexing harmonic sensor at different interrogating distances.

all the measurement conditions remain the same. It is evidently seen that the peak frequency in the FHSS pattern remains unchanged, regardless of the interrogation range. Therefore, the FHSS pattern analysis provides an absolute accuracy sensing with high robustness and reliability. This is, however, impossible for a typical passive harmonic tag that detects the RSSI amplitude at a constant operating frequency. In addition, the redundant information from extra dimensions can tolerate the variation in other factors, such as the sensor location and interferences from near-field objects. The maximum detection range is ~ 4.0 m for a given noise floor of -70 dBm. The maximum range is expected to be increased by adjusting configurations of the spectrum analyzer with reduced noise floor and/or by optimizing antennas and circuits used in the harmonic tag.

Next, to demonstrate the multiplexed sensing capability of the proposed wireless sensor, we have conducted sensing experiments for three different scenarios, which are as follows: (A) Channel 1 is filled with the SUT and Channel 2 is empty; (B) Channel 1 is empty, and Channel 2 is filled with the SUT; and (C) both fluidic channels are filled with SUTs. Here, the important parameters used in this measurement setup are as follows: $P_t = 25$ dBm, $R_1 = R_2 = 1.3$ m, $G_T = 10.5$ dBi at 1.4 GHz, $G_R = 16.5$ dBi at 2.8 GHz, and the liquid volume of SUT is set to $100 \mu\text{L}$ (i.e., the total volume of the fluidic channel). Fig. 10 reports the measurement results for the sensing scenario A. It is seen from Fig. 10(a) that by injecting acetone–water mixtures of different concentrations into Channel 1, the first RSSI peak in the FHSS pattern can be shifted from 2.28 to 2.07 GHz, whereas the second RSSI peak is locked at 3.25 GHz, as summarized in Fig. 10(b). On the other hand, for scenario B, the first RSSI peak remains unchanged, whereas the second RSSI peak is downshifted from 3.11 to 2.6 GHz, as can be seen from Fig. 11(a) and (b). The measured results in Figs. 10 and 11 clearly indicate that multiplexed sensing with good isolation may be possible with the proposed compact, fully passive harmonic sensor. Fig. 12 reports the measurement results for the sensing scenario C, where the harmonic sensor is exploited to simul-

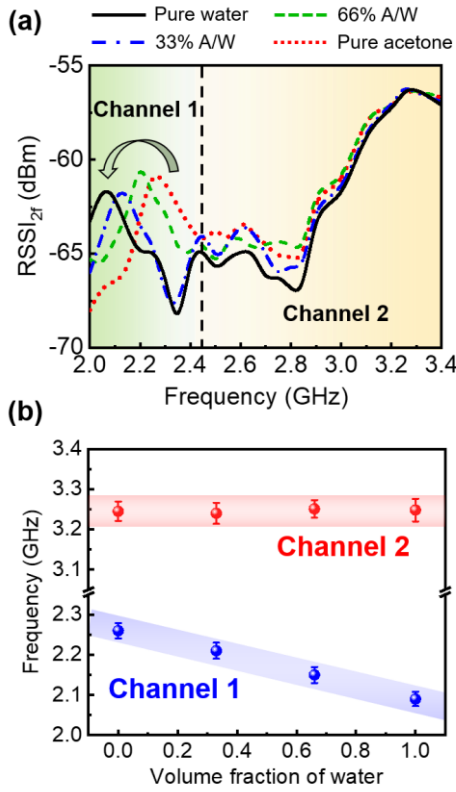


Fig. 10. (a) Measured FHSS pattern of the multiplexing harmonic sensor, of which Channel 1 is injected with SUT and Channel 2 is empty (sensing scenario A). (b) Peak frequency extracted from the FHSS pattern for different volume fractions of water in the acetone–water mixture.

taneously monitor two SUTs. It is seen from Fig. 12 that when acetone–water mixture of different concentrations are injected into the two fluidic channels, the first RSSI peak is shifted from 2.27 to 2.09 GHz. Besides, the second one is also shifted from 3.12 to 2.61 GHz. Such results further confirm robustness and multiplexed sensing ability of the proposed harmonic sensor in noisy environments. For different injected SUTs, the peak RSSI strength may slightly change because the dielectric constants and loss tangents of them could be different. The loss tangent fitted from the measurement result is 0.025 for pure acetone and 0.04 (0.055) for the mixture with $A/W = 66\%$ (33%) and is increased to 0.075 for pure water. Increasing the SUT's dielectric loss (i.e., increase the volume fraction of water) may decrease the quality factor (Q -factor) of the ESA, which in turn reduces the peak RSSI value and increases the linewidth of the FHSS pattern, as can be seen from Figs. 10–12.

Finally, we notice that this harmonic sensor was manufactured using a single-layer Rogers 5880 substrate with a thickness of only 0.5 mm, thus allowing good flexibility. We have deployed the flexible harmonic tag on an empty dielectric tube [polyvinyl chloride (PVC) pipe with radius $r = 10$ cm and relative permittivity $\epsilon_r = 2.3$ at 2.6 GHz], as shown in Fig. 13(a) and (b). In this case, the tag has a $\pm 30^\circ$ bending angle, and the injected liquid volume is 100 μL . The same bistatic telemetry setup was used to measure the FHSS patterns

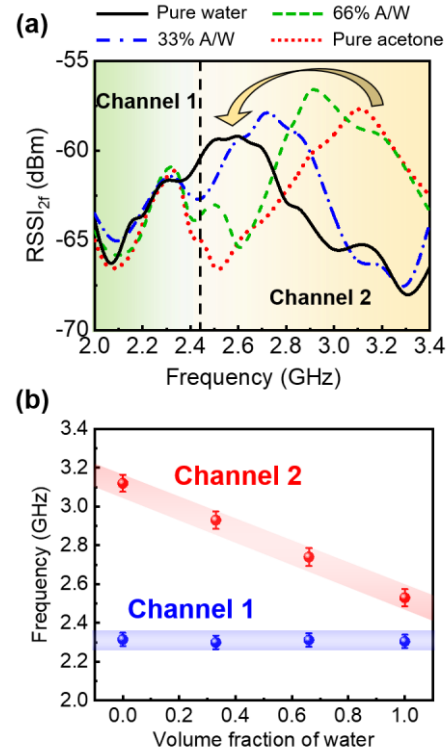


Fig. 11. (a) and (b) Similar to Fig. 9(a) and (b), but for the sensing scenario B where Channel 2 is injected with the acetone–water mixture of different concentrations and Channel 1 is void.

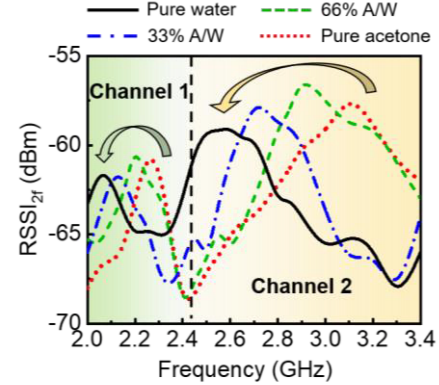


Fig. 12. Similar to Fig. 9, but for the sensing scenario C, where both fluidic channels are filled with mixtures of different concentrations.

of the harmonic tag attached conformally to the PVC tube. Fig. 13(c) reports the normalized peak frequency extracted from the FHSS patterns for water–acetone mixtures with different water volume fractions; here, three different bending angles were tested. From Fig. 13(c), it is seen that bending the harmonic tag does not affect the sensing performance, which once again proves the robustness of our prototype in withstanding a moderate range of bends. The sensitivity and resolvability of the proposed device can be defined as the slope of the peak RSSI frequency versus the water volume fraction [see Fig. 13(c)], which are obtained as 2.1 MHz/1% for Channel 1 and 5.1 MHz/1% for Channel 2. Such results

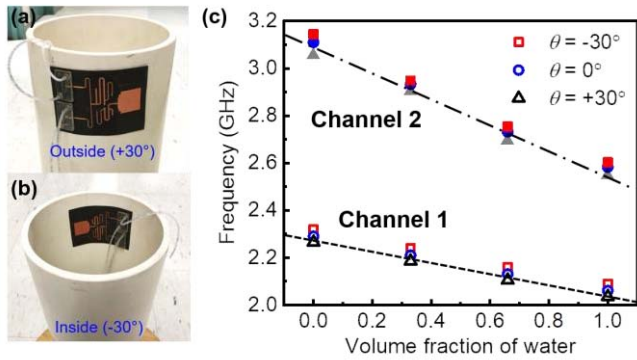


Fig. 13. Conformal multiplexing harmonic tags attached to a dielectric tube at a bending angle approximately equal to (a) $+30^\circ$ and (b) -30° . (c) Peak frequency of the FHSS patterns against the volume fraction of water in the acetone–water mixture for sensing scenario C (the results for $\theta = 0^\circ$ can be seen from Fig. 11).

suggest that for a $100\text{-}\mu\text{L}$ microfluidic reservoir, $\pm 1\%$ change in the volume fraction of water may be detected using a standard spectrum analyzer with a 10-kHz resolution bandwidth. As an example, the flexible harmonic tag can be deployed on the PVC pipes in the plumbing system [see Fig. 13(a)], for which plastic tubes can guide SUTs from different nodes into specific channels. In addition, a plastic tube carrying environmental mixtures (e.g., water mixed with microplastics, microfibers, detergents, and hydrogen peroxides) can be connected to microfluidic separation and sorting cells for delivering a specific SUT to its assigned channel. In general, the ratio of dielectric constant between these agents and pure water is greater than that between acetone and water. Ideally, an array of narrow-band ESA and liquid channels can be realized for multiplexed sensing purposes. We should point out that this conformal wireless sensor with high sensitivity and good linearity may have potential applications in healthcare, medical, and biological monitoring systems, such as the lab-on-a-chip and POC, as well as industrial and environmental monitoring, such as oil tube crack detection or water tube leakage monitoring. The SUT is not limited to acetone–water mixtures, but can also be extended to a variety of widely used solutions, such as ethanol–water and glucose–water.

IV. CONCLUSION

We have demonstrated a compact, low-profile, and fully passive harmonic transponder with the scalable and multiplexed sensing capability. By hybridizing this harmonic transponder with microfluidic channels, we have built a zero-power multiplexing harmonic sensor and have demonstrated its ability to rapidly and contactlessly monitor properties of aqueous solutions in a noisy indoor environment. Comparing to the traditional linear backscatter RFID tags, the proposed harmonic-based telemetry configuration may offer enhanced robustness and reliability in real-world applications. We envision that such multiplexing harmonic tags may be integrated with system-level microfluidic networks (e.g., sorting cells and diagnostic assays) to maximize its potential for wireless sensing and

telemetry, lab-on-a-chip measurements, rapid healthcare tests (e.g., POC tests and drive-through tests), Industry 4.0, and IoTs.

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