A Flexible PVDF-based Platform Combining Acoustofluidics and Electromagnetic Metamaterials

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***Abstract*—Acoustofluidic devices have been demonstrated effectively for liquid manipulation functionalities. Likewise, electromagnetic metamaterials have been employed as highly sensitive and wireless sensors. In this work, we introduced a new design combining the concepts of acoustofluidics and electromagnetic metamaterials on a single device realised on a flexible PVDF substrate. We characterise the operation of the device at acoustic and microwave frequencies. The device can be used in wearable biosensors with integrated liquid sampling and continuous wireless sensing capabilities.**

Keywords—metamaterials; surface acoustic waves; PVDF

I. INTRODUCTION

A major focus in wearable biosensing technology is on the development of devices and methods to realise liquid manipulation, highly sensitive detection and wireless operation on flexible platforms. Although these functionalities have been demonstrated using individual devices, the need for a comprehensive approach to integrate these functionalities and beyond on a single platform towards a next generation of wearable devices still remains. Among different technologies, acoustofluidic devices have been proven to be effective for liquid manipulation and actuation with some promise to realise sensitive detection and wireless operation [1,2]. On the other hand, electromagnetic metamaterials offer excellent capabilities for sensitive and wireless detection [3,4].

In this work, we show the feasibility for a wearable sensing platform integrating two emerging technologies: electromagnetic metamaterial sensors and piezoelectric polymer-based acoustofluidic actuators on a single device. This platform will enable us to address three key challenges for future wearable devices: i) wireless and sensitive detection; ii) liquid manipulation and actuation; iii) personalisation. Metamaterials will enable fast, accurate, and wireless sensing capabilities, whereas piezoelectric polymers will enable liquid actuation capabilities with energy harvesting options in flexible implementations. There has been significant amount of work recently for the development of these individual technologies, however, our research is focused on the integration of these technologies on a single device for the development of a new affordable, scalable, and customised platform for wearable devices. In this work, we used polyvinylidene fluoride (PVDF) metallised with patterned electrodes to realise the devices.

PVDF is a functional piezopolymer that has found several applications, such as an electrical insulator, a binder in lithium ion batteries or as a membrane for protein blotting attributed to its distinct chemical, mechanical, and electrical properties. Additionally, the piezoelectric properties of PVDF have been exploited for manufacturing electroacoustic transducers, tactile sensors, and actuators [5]. Unlike its state-of-the-art stiff and fragile piezoelectric material counterparts, PVDF can be easily shaped and is suitable for bending, a requirement for wearable sensors. Another advantage of PVDF is that its mechanical and electric properties can be tailored by copolymerizing PVDF with monomers such as trifluoroethylene (TrFE), chlorotrifluoroethylene (CTFE) and HFP (hexafluoropropylene). PVDF is also a piezoelectric building block in magnetically coupled piezoelectric devices and magnetoelectric composites.

II. DESIGN AND FABRICATION OF THE DEVICES

Surface acoustic wave (SAW) resonators are one of the building blocks of acoustofluidic devices where a metallised interdigitated transducer (IDT) is defined on a piezoelectric substrate.

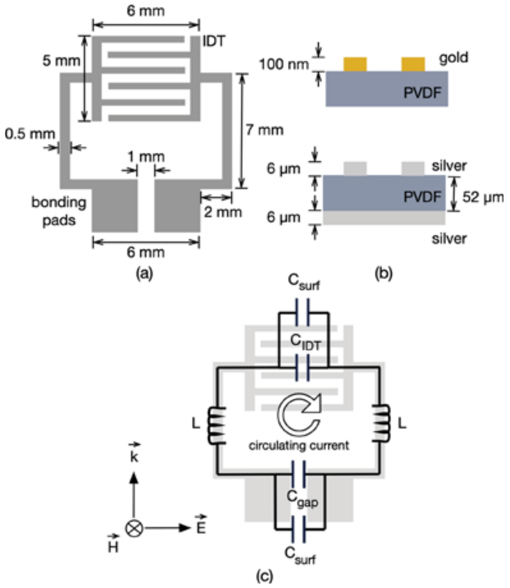

Fig. 1. (a) Schematics of the metallised layer on a PVDF substrate, (b) cross-sectional overview of the fabricated devices, (c) induced circulating

current and the equivalent circuit of the device operating as an electromagnetic metamaterial.

The characteristics of the resonator are determined by the geometry of the IDT and are relatively independent to the geometry of the conductors connecting the IDT to the bonding pads where electrical connection is made. Careful design of the conducting line, bonding pad and the IDT can define an electromagnetic resonator at the resonant frequency of which induced current can circulate as we demonstrated recently [6]. Fig. 1(a) shows a design where we designed the metallic layer to serve both functionalities. The IDT comprises 20 pairs of fingers with a wavelength of 300 µm to generate surface acoustic waves on the PVDF substrate. We fabricated two variations of devices using a single gold layer sputtered on a PVDF layer and double silver ink layers on another PVDF layer as shown in Fig. 1(b). Under an electromagnetic field excitation, the metallic structure electrically forms an LC resonator at its magnetic resonance as schematically shown in Fig. 1(c). A circulating resonant current is induced along its surface with its resonant frequency being determined by the geometry of the structure. The inductance (L) is given by the conductor geometry, the capacitance is determined by the gap (C_g), the IDT (C_{IDT}) and the surface (C_s) of the structure. These resonators in centimetre to millimetre-scale are usually used for applications in microwave bands, exhibiting very sharp resonant behaviour with quality factors larger than 1,000 unlike conventional types of passive resonators [7]. Owing to high quality factors, the change in resonant frequency of an SRR structure can effectively be used as a sensing mechanism, which can be induced by a change in dielectric properties of the medium and the geometry of the structure.

III. CHARACTERISATION OF THE DEVICES

We characterised the acoustic and electromagnetic characteristics of the fabricated devices. First, we measured the reflection spectra (S_{11}) of the devices at acoustic frequencies by connecting the bonding pads to a vector network analyser. Fig. 2 shows the fundamental resonant frequency of the PVDF/silver-electrode device is 3.2 MHz. This corresponds to a speed of sound in the PVDF sample as 960 m/s.

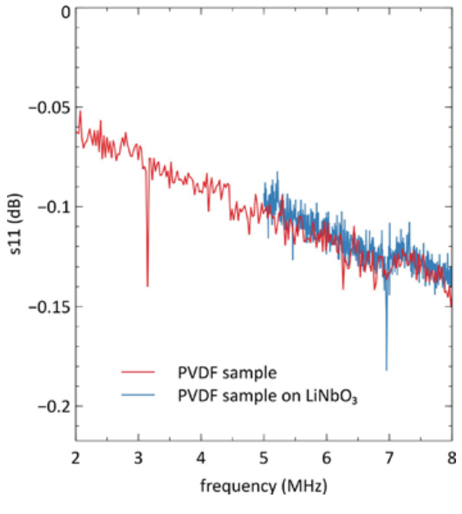

Fig. 2. S11 spectra of the PVDF/silver-electrode device measured between the bonding pads

We repeated this measurement after placing the PVDF sample on top of a LiNbO$_3$ plate. The resonant frequency is shifted to 7 MHz, corresponding to a speed of sound of 2100 m/s. The PVDF film is thin and travelling waves can be transmitted to the LiNbO$_3$ plate resulting in increased frequency and effective speed of sound.

In addition to acoustic characterisation, we excited the devices electromagnetically using a pair of monopole antennas to measure the electromagnetic resonant frequency of them. We used monopole patch antennas that are 26 mm in length and 3 mm in width, realised on a 35 µm-thick Cu layer on a PCB substrate. We connect the antennas to the ports of a vector network analyser to excite the device electromagnetically and to measure the transmission (S_{21}) spectra of the devices between the antennas. Fig. 3 shows the S21 spectrum of a device with a fundamental resonant frequency of 3.4 GHz and a quality factor of 300.

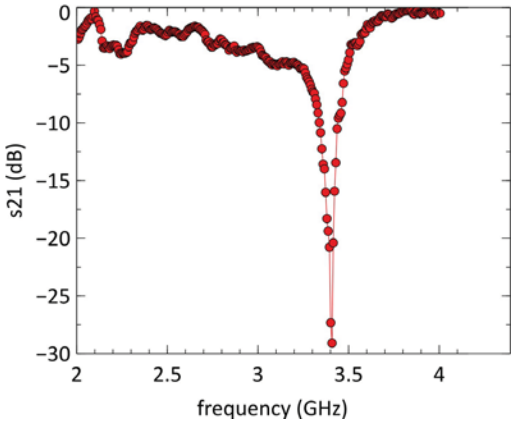

Fig. 3. S21 spectra of the PVDF/gold-electrode device measured using a pair of monopole antennas connected to a vector network analyser.

The measured electromagnetic resonant frequency of the device corresponds to a case where circulating current is induced along the conducting path shown in Fig 1(c). We investigated the electromagnetic resonances based on different excitations of the device as shown in Fig 4 using an electromagnetic simulator (CST Microwave Studio). When the electric field is along the gap (Fig. 4(a) and Fig. (b)), the field can polarise the opposing pads resulting in a circulating current. Likewise, when the magnetic field is normal to the device (Fig. 4(b) and Fig. 4(c)), a circulating current is induced. In addition, when the electric current is also perpendicular the fingers (Fig. 4(c)), the alternating fingers can be polarised resulting in complex current paths on the IDT area. This excites additional resonances as observed in Fig. 4(c). When neither the magnetic field is normal to the device nor the electric field polarises the gap, no resonance is observed within the range of 3-4.5 GHz (Fig. 4(d)).

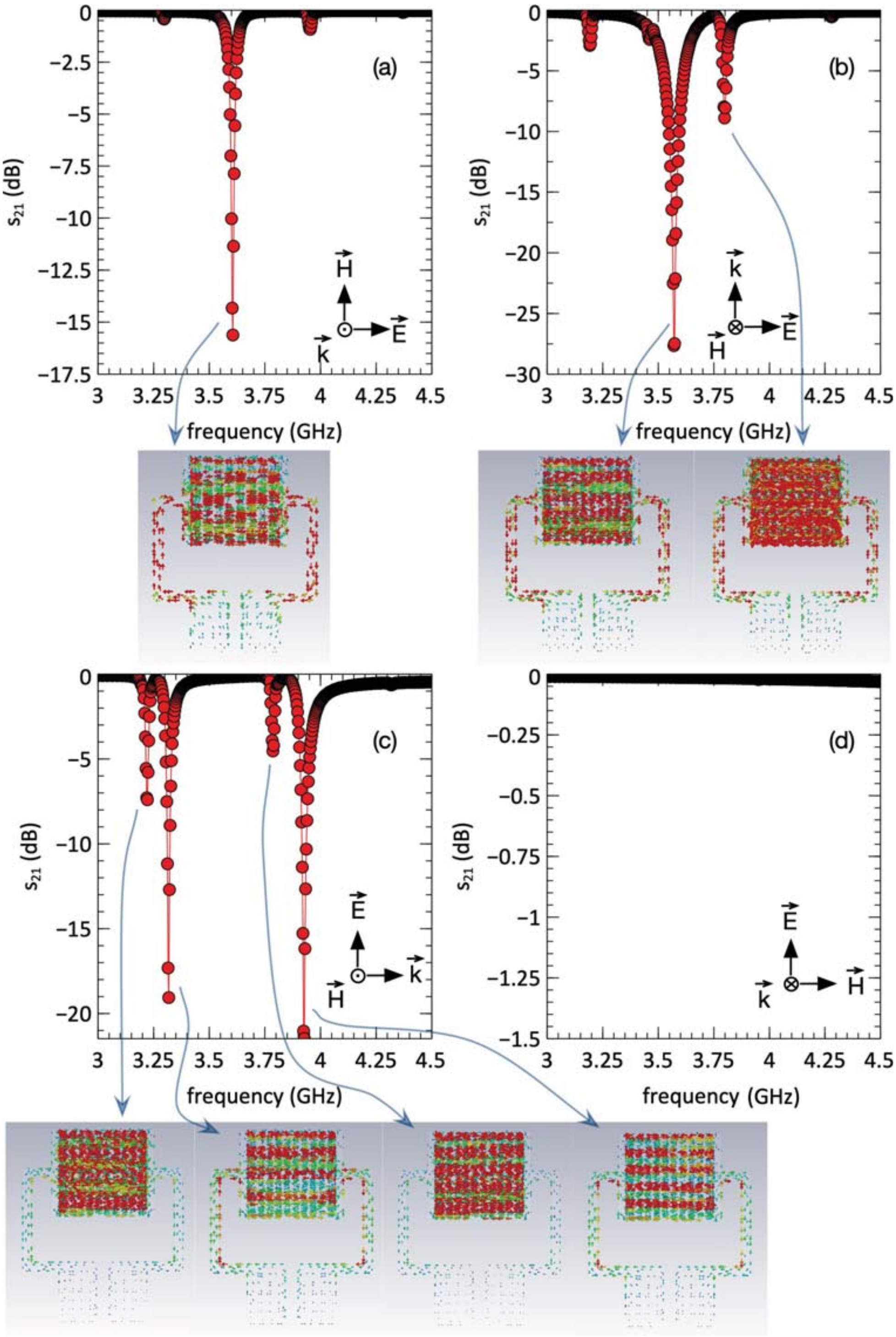

Fig. 4. Simulated electromagnetic resonances of the device with different excitation conditions.

IV. CONCLUSIONS

In this work, we introduced a new design combining surface acoustic waves and electromagnetic metamaterials on a single device realised on a PVDF substrate. The device exhibits an acoustic resonance at 3.2 MHz and an electromagnetic resonance at 3.4 GHz. The acoustic resonance can be used for liquid manipulation whereas the electromagnetic resonance can be used for sensing functionalities.

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REFERENCES

[1] Y.Q. Fu, J.K. Luo, X.Y. Du, A.J. Flewitt, Y. Li, G.H. Markx, A.J. Walton, and W.I. Milne, “Recent developments on ZnO films for acoustic wave based bio-sensing and microfluidic applications: a review,” Sensor. Actuat. B-Chem., vol. 143, pp 606-619, 2010

[2] P. Zhu and L. Wang, "Passive and active droplet generation with microfluidics: a review," Lab. Chip., vol.17, pp 34-75, 2017.

[3] T. Chen, S. Li, and H. Sun, “Metamaterials application in sensing,” Sensors., vol. 12, pp 2742-2765, 2012.

[4] A. Salim and S. Lim, “Review of recent metamaterial microfluidic sensors,” Sensors., vol. 18, pp 232, 2018.

[5] B. Stadlober, M. Zirkl, and M. Irimia-Vladu, “Route towards sustainable smart sensors: Ferroelectric polyvinylidene fluoride-based materials and their integration in flexible electronics," Chem. Soc. Rev., vol. 48, pp 1787-1825, 2019.

[6] S. Zahertar, Y. Wang, R. Tao, J. Xie, Y. Q. Fu, and H. Torun, “A fully integrated biosensing platform combining acoustofluidics and electromagnetic metamaterials,” J. Phys. D. Appl. Phys., vol. 52, 485004, 2019.

[7] H. Torun, F. Cagri Top, G. Dundar, and A. D. Yalcinkaya, “An antenna-coupled split-ring resonator for biosensing,” J. Appl. Phys., vol. 116, 124701, 2014.