Sensors and Actuators A 190 (2013) 136–140

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Transparent force sensing arrays with low power consumption using liquid crystal arrays

Chia-Yi Huang, Liang Lou, Aaron J. Danner, Chengkuo Lee*

Department of Electrical & Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576, Republic of Singapore

ARTICLE INFO

Article history:
Received 27 June 2012
Received in revised form 1 October 2012
Accepted 23 October 2012
Available online xxx

Keywords:
Liquid crystals
Force sensor
Tactile sensor
Transparent

ABSTRACT

A transparent force sensing array with low power consumption is developed from a 3 × 3 liquid crystal (LC) array. As force is applied to the LC array, the force-dependent capacitance curve of a sensor pixel under a higher voltage will shift to larger capacitance. Accordingly, the force range of the LC array can be divided into many sub-ranges at one of the capacitance values. The number of the input voltage is equal to that of the output capacitance in each of the sub-ranges, and the voltage-to-capacitance number is small (large) in the high (low)-force sub-range. The sensing array measures force in terms of the voltage-to-capacitance number. The transparent force sensing array shows potential as a touch panel, while it is immune to the need of rectifying the nonlinear relation between the applied force and the output capacitance using complex algorithm via high-end microcontrollers.

1. Introduction

Touch panels have attracted considerable attention in mobile devices due to their intuitive operation and immunity to use any additional input devices such as mice or keyboards. Recently, in-cell touch technology which integrates touch devices into liquid crystal (LC) panels has been proposed [1–6]. This technology brings the LC panels with touch function and makes the touch LC panels slim and lightweightover add-on-type touch panels since it does not need to bind and assemble the touch devices and LC panels. The touch LC panels detect force through the measurement of light intensity, resistance or capacitance, and these approaches still exhibit many challenges on resolution, reliability, fabrication, and low power consumption. Up to now, mobile devices such as smart phones and tablet personal computers could not sustain a long-term operation time because the touch LC panels in the mobile device consume most of battery energy. An intriguing approach to extend the operation time of a mobile device is to develop touch LC panels with low power consumption for mobile devices.

In this paper, we develop an LC cell with elastic spacers for investigation of the dependence of capacitance versus force under various bias voltages. By using a gray scale sensing concept, the LC cell provides the information of gray scale number, giving voltage-to-capacitance relationship, derived from the force-dependent capacitance curve to measure objects of mass ranging from 0 to 14.3 g. As such, it avoids a need to rectify the nonlinear relation between the applied force and the output capacitance using complex algorithm via high-end microcontrollers [7,8]. Because of no microcontroller used, the proposed LC cell has potential to be developed into a touch panel with low power consumption. A 3 × 3 array by the dependence is made to demonstrate its commercialization viability. The LC array can determine force up to 360 mN and provides several promising features such as transparency, easy fabrication, low cost, and low power consumption.

2. Preparation of LC cell and array

An LC cell with elastic spacers is used to study the dependence of capacitance on force at the various voltages. The LCs are used because its capacitance can be controlled by varying the applied voltage to it. The elastic spacers are used to enhance the deformation of the cell gap in order to obtain the obvious variation in the capacitance of the LC cell. An empty cell is fabricated using an indium tin oxide (ITO) glass and an ITO polyester (PET) film, and they are separated by two elastic spacers of approximately 33 μm thick, as shown in Fig. 1(a). The ITO glass and PET film are pre-coated by polyvinyl alcohol (PVA) and rubbed in anti-parallel directions to form a homogeneously aligned cell. The elastic spacers are made from a mixture of polydimethylsiloxane (PDMS) prepolymer and its curing agent (Sylgard 184A and 184B, Dow Corning Co.) at a ratio of 10:1. After that, LCs (E7, Merck Co.) are injected into the empty cell. To frame the LCs, epoxy glue is used to seal the LC cell. Finally, the homogeneous alignment in the LC cell is verified using a conoscope.

* Corresponding author. Tel.: +65 6516 2244; fax: +65 6516 7912.
E-mail address: elelc@nus.edu.sg (C. Lee).

0924-4247/$ – see front matter
http://dx.doi.org/10.1016/j.sna.2012.10.031

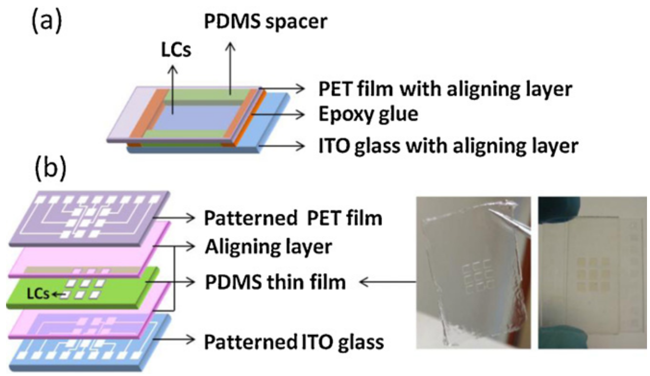

Fig. 1. (a) Schematic drawing of LC cell with elastic spacers. (b) Schematic diagram of LC array.

A 3 × 3 LC array is fabricated to realize a force sensing array. Fig. 1(b) shows the schematic diagram of the LC array. The structure of the LC array consists of a patterned ITO PET film/aligning layer/PDMS thin film with square holes/aligning layer/patterned ITO glass. The ITO electrode structures on the PET film are patterned by oxalic acid with photoresist as the etching mask. Similar patterning process is also used to create the ITO electrode patterns on the glass substrate. The PDMS film with square holes is fabricated by SU-8 mold processing, and the thickness of the film is about 65 μm. The dimension for each hole is 2 mm × 2 mm, and the distance between any two neighboring pixels is 1 mm. The PDMS film with the square holes plays a key role in the development of the multi-pixel force sensing array. A common clamping method is used to fabricate the PDMS film in this study [9]. By using such method, the dimension of the square holes can be reduced to 100 μm × 100 μm in future work [9]. The PDMS film is bonded on the ITO glass by oxygen plasma, and the square holes are filled with the E7 LCs. After the ITO PET is bounded on the PDMS film, the 3 × 3 LC array is formed.

The bonding of hydrophobic PDMS and hydrophilic PVA is not good in many cases. In our case, the oxygen plasma treatment makes PDMS hydrophilic [10]. By using this treatment, the PDMS molecules are able to bond with the PVA molecules due to hydrogen bonding. However, the hydrogen bonding in the LC array becomes weak after ∼100 times of testing and induces the array to lose its functions. The authors will improve the samples in the future.

3. Experimental setup

A force instrument with 1 mN resolution (Instron 5548) is used to determine the force that is applied to the LC cell, as shown in Fig. 2. A round flat-headed copper probe (diameter = 4 mm) is mounted on the sample holder of the force instrument so as to press the PET film while the LC cell is fixed on the translational stage of the instrument via a piece of double-side tape. As the LC cell touches the copper probe by the translational stage, the sensor of the force instrument located at the side of the sample holder can measure the force that is applied to the cell. Due to the adhesion force of the tape, the weight of the device is not considered in the force measurement. The capacitance is measured by an LCR meter (Agilent 4284A) at an AC probe voltage (50 mV, 1 kHz) superimposed on a DC driving voltage.

4. Results and discussion

Fig. 3 shows the force-dependent capacitance curves of the LC cell at the various voltages, V = 0 V, 1.0 V, 1.8 V, 2.0 V, 2.2 V, 2.4 V, 2.6 V, and 2.8 V. In the each case of the applied voltages, the capacitance of the LC cell increases with the force exerted by the copper probe on the PET film. This is attributed to the fact that the LC cell can act as a plate capacitor. The capacitance formula for the LC cell is expressed as:

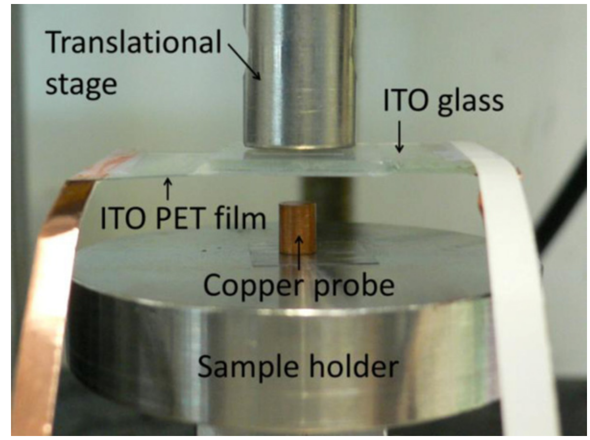

Fig. 2. Experimental setup for the dependence of capacitance on force at the various voltages.

$$C = \varepsilon_{\mathrm{eff}} \frac{A}{d} \quad (1)$$

where $\varepsilon_{\mathrm{eff}}$ is the effective dielectric constant of the LCs; A and d refer to the area and thickness of the LC cell, respectively. As the force is applied to the LC cell, the thickness (area) of the LC cell decreases (increases) since the LCs are incompressible and the PDMS spacer is elastic. Accordingly, an increase in the force makes the capacitance larger. Regarding the force-dependent capacitance curves at V = 0 V and 1 V are superimposed because the threshold voltage of the LC cell is close to 1.0 V [11]. The LC cell can measure force because the capacitance of the cell changes upon touching it. When there is no applied voltage, the sensitivity in force is 0.34%/mN for the LC cell. The force sensitivity derived in our investigated LC cell is higher than those reported data, i.e., 0.016%/mN [12] and 0.19%/mN [13]. However, the LC cell is unlikely to be commercially successful products since the relation between the input force and the output capacitance requires a calibration process to rectify the nonlinear correspondence using complex algorithm via high-end microcontrollers [7,8]. Such calibration procedures lead the LC cell to consume a lot of energy. An improved approach to reduce

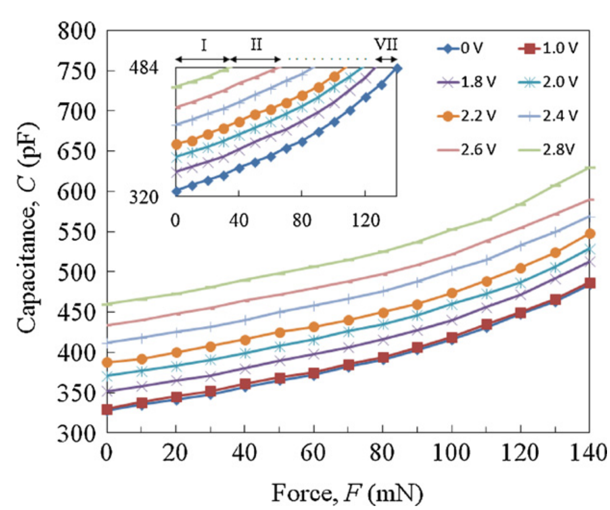

Fig. 3. Force-dependent capacitance curves of the LC cell at the various voltages. The inset shows 7 continuing sub-ranges from I to VII as C = 484 pF is set as the maximum.

Table 1
Boundaries for the 7 force sub-ranges.

Sub-region	I	II	III	IV	V	VI	VII
Boundaries (mN)	$0 < F \le 34$	$34 < F \le 65$	$65 < F \le 87$	$87 < F \le 107$	$107 < F \le 118$	$118 < F \le 126$	$126 < F \le 140$

the power consumption of the LC cell will be presented in next paragraph.

In experiments, we observed that the capacitance signal changes into a resistive nature due to the contact of the two conductive substrates, when the applied force is larger than 140 mN. Therefore, the maximum detectable force for the LC cell is 140 mN based on our current setup. The limitation on the force sensing range may be overcame by using a different ratio of PDMS prepolymer and its curing agent, as the Young's moduli of the polymer mixture changes according to the composition in it [14]. The force-dependent capacitance curve shifts to larger capacitance with the increase of the applied voltage in Fig. 3. It is attributed to the fact that the effective dielectric constant of the LCs can be controlled by varying the applied voltage. The effective dielectric constant of the LCs, ε_{eff}, can be written as:

$$\varepsilon_{\text{eff}}(\theta) = \varepsilon_{\perp} \sin^2\theta + \varepsilon_{//}\cos^2\theta \quad (2)$$

where θ is the angle between the probe electric field and the LC director; $\varepsilon_{\perp}$ and $\varepsilon_{//}$ are the dielectric constants in directions perpendicular and parallel to the probe electrical field. As a DC voltage is applied to the LC cell, the AC probe electrical field experiences an increment of the effective dielectric constant of the LCs. This is due to the LC director being reoriented toward the direction parallel to the AC electrical field. Therefore, an increase in the applied voltage makes the force-dependent capacitance curve rising. The force sensing range from 0 to 140 mN can be divided into many continuing sub-ranges at one of the capacitance values. For example, the LC cell exhibits 7 continuing sub-ranges (the inset of Fig. 3), where the maximum value of capacitance is set as 484 pF which refers to the conditions of $V = 0$ V and the maximum force that the LC cell can afford. In each of the 7 sub-ranges, the number of the input voltage is equal to that of the output capacitance, and the voltage-to-capacitance number is small (large) in the large (small)-force sub-range. Thus the voltage-to-capacitance number is taken as a gray scale sensing approach to estimate the applied force with reasonable resolution. Table 1 lists the boundaries for the 7 force sub-ranges. These boundaries are determined by measuring the forces, which corresponds to $C = 484$ pF at $V = 0$, 1.8, 2.0, 2.2, 2.4, 2.6, and 2.8.

Fig. 4 illustrates the force measurement of 2.0, 10.0 and 12.6-g objects. The measurement is performed by the LCR meter and a computer with the LabVIEW software. The code in the LabVIEW program instructs the LCR meter to apply the 7 voltages to the LC cell, and it receives the voltage-dependent capacitance from the LCR meter. If the capacitance is larger than 484 pF, the program will regard it as 0 pF. As such, the voltage-to-capacitance number can be obtained from the LabVIEW program. The round flat-headed copper probe (mass: 0.6 g) is used to load the three objects with different areas in order to hold the same contact area as the setup of Fig. 2. In Fig. 4, the voltage-to-capacitance numbers are 7, 4 and 1 for the 2.0 g, 10.0 g and 12.6 g objects, respectively. According to the inset of Fig. 3 and Table 1, the numbers 7, 4 and 1 correspond to the force regions I (0–34 mN), IV (87–107 mN) and VII (126–140 mN), respectively. The gravitational forces associated with the weights of 2.0, 10.0 and 12.6-g objects added on the 0.6-g copper probe are about 25.5, 103.4 and 129.4 mN, which are within the region I, IV and VII, respectively. This result indicates that the LC-based force sensor can measure normal force by identifying the voltage-to-capacitance number. When more voltage-to-capacitance curves are investigated for applied voltages between 1.0 V and 2.8 V, it may enhance the resolution of force measurement in this method. The measurement avoids a need to create a function for transferring the capacitance into the force.

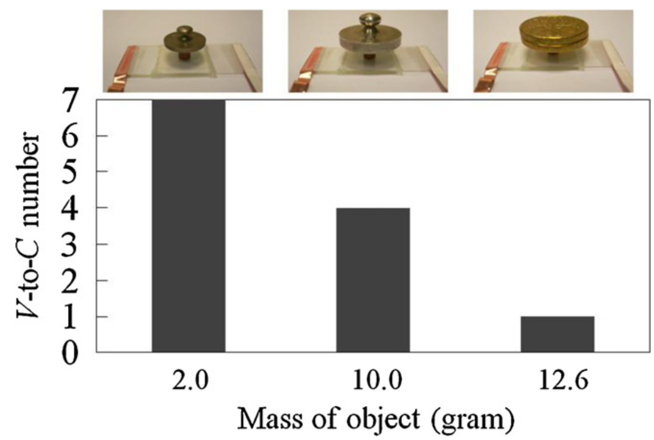

Fig. 4. Measurement of 2.0, 10.0 and 12.6-g objects by the LC-based force sensor. A 0.6-g copper probe is used to load the objects.

As there is no force applied to the LC cell with 33-μm-thick cell gap, the measured response time values (equal to the addition of the decay time and the rise time) are 1.75 s and 1.23 s at $V = 1.8$ and 2.8 V, respectively (not shown herein). The two experimental values approach the theoretical response times [15], 1.58 s at $V = 1.8$ V and 1.10 s at $V = 2.8$ V, where the LCs used for calculation is Merck E7 whose physical parameters are listed as follows: rotation viscosity $\gamma_1 = 140$ mPa s, bend elastic constant $K_{33} = 17$ pN, and dielectric anisotropy $\Delta\varepsilon = 13.8$. Although the measured response time of the LC cell is slow under no force, it is fast when a force is applied to the cell. It is attributed the fact that the decay time of the LC cell is directly proportionate to the square of the cell gap [15]. In future study, the cell gap could be reduced so as to achieve a faster response time.

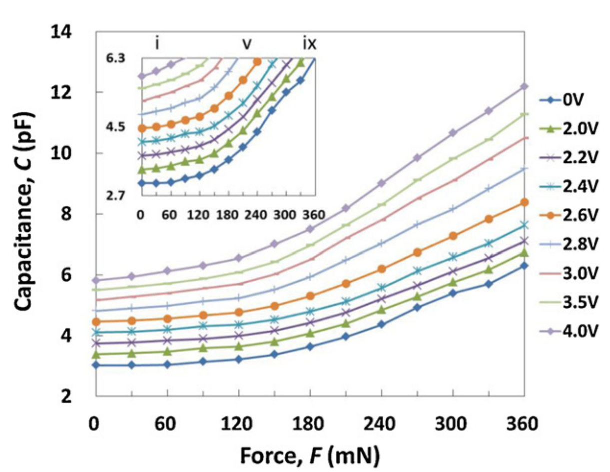

Fig. 5. Force-dependent capacitance curves of the 9 pixels, where the 9 voltages are applied to the pixels individually. The inset shows 9 continuing sub-ranges from i to ix as $C = 6.3$ pF is set as the maximum.

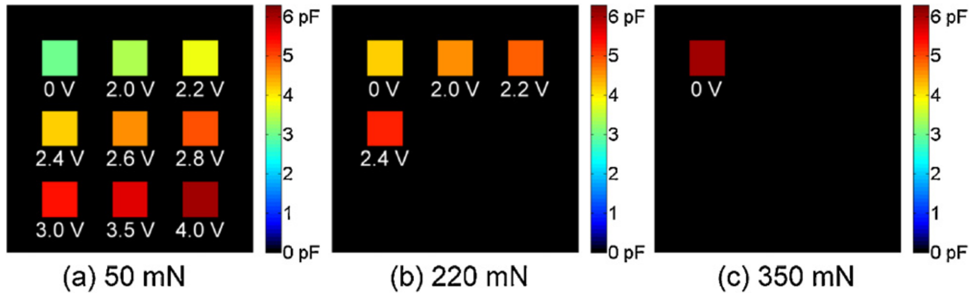

Fig. 6. Force measurement by the 3 × 3 LC array: (a) 50 mN; (b) 220 mN; (c) 350 mN.

5. Application

The 3 × 3 LC array is used to demonstrate its commercialization viability. Fig. 5 shows the force-dependent capacitance curves of the 9 pixels, where 9 voltages, V = 0 V, 2.0 V, 2.2 V, 2.4 V, 2.6 V, 2.8 V, 3.0 V, 3.5 V and 4.0 V, are applied to the pixels individually. These curves are obtained by the LCR meter and force instrument. A square flat-headed metal probe (side length = 10 mm) is used to press the 9 pixels. The result of Fig. 5 is similar to that of Fig. 3, and it demonstrates that the LC array is able to act as a force sensing array. The maximum detectable force for the LC pixels is 360 mN based on the current setup. The LC array exhibits 9 continuing subranges (the inset of Fig. 5) as the capacitance C = 6.3 pF is set as the maximum value.

Fig. 6 illustrates the force measurement results of the LC array. The capacitance values of the 9 pixels are measured in a one-by-one manner. The code in the LabVIEW program instructs the LCR meter to apply the 9 voltages to the 9 LC pixels individually, while it receives the capacitance values of the pixels from the LCR meter. If the capacitance is large than 6.3 pF, the LabVIEW program will regard it as 0 pF. A MATLAB program is used to transfer the modified capacitance values into a color scale image, and the highest scale of color is set as 6.3 pF. In Fig. 6, there are 9, 5 and 1 colorful elements for the forces of 50, 220 and 350 mN, respectively. According to the inset of Fig. 5, the 9, 5 and 1 colorful elements correspond to the force regions i (0–90 mN), v (200–245 mN) and ix (340–360 mN), respectively. This result indicates that the LC array can measure normal force by the color scale images.

The proposed LC cell or array needs a readout system to measure the applied force. For the 3 × 3 LC array, the readout system should include a capacitance measurement circuit, a voltage comparison circuit and a display. The capacitance measurement circuit converts the charge output from the LC pixels into 9 voltages [16]. The comparison circuit, which is composed of some comparators (such as LM311 and LM339), is used to compare the 9 voltages with a specified voltage, generating the output signals. The number of the output signals determines the applied force, and will be shown in the display. In the reported force sensors [13–16], the force measurement needs complex algorithm by high-end microcontrollers to rectify the nonlinear relation between the applied force and the output signal [7,8]. Such a measurement may cause high power consumption during the dynamic detection. In this study, the proposed LC cell or array which measures force by a gray scale sensing concept may be low power consumption on the force measurement because the readout system uses a simple hardware circuit consisting of comparators rather than the complex algorithm by the high-end microcontrollers.

For the future application on the touch panels, we need to improve the resolution of the pixels, including the increase of the pixel numbers and the decrease of the pixel size. However, a higher resolution will slow down the response time of the sensor in a specific algorithm of seeking the voltage. In order to improve this point, the resolution of the pixels cannot be too high, while this reduction in the pixel resolution will result in a measured force accuracy tradeoff. Fortunately, the pixel resolution and the force accuracy just need to meet the fingers because they are always used to touch the panel.

6. Conclusions

This work provides an improved approach to reduce the power consumption of the LC cell and array because they avoid a need of using a high-end microcontroller to rectify the nonlinear relation between the applied force and the output capacitance. The LC cell measures the mass of objects from 0 to 14.3 g, while the LC array can determine the applied force up to 360 mN. Both of them measure force based on the gray scale sensing mechanism in terms of voltage-capacitance number. Furthermore, the LC array demonstrates its commercialization viability by transferring the voltage-capacitance number into the color scale image. The LC cell and array provide several advantages such as transparency, easy fabrication and low cost; they have potential to be developed into touch panels with low power consumption for next generation operating systems.

Acknowledgements

This work is partially supported by research grant of SERC Grant No. 0921010049 from A*STAR, Singapore, Faculty Research Committee (FRC) Grant (R-263-000-692-112) at the National University of Singapore, and the NRF-CRP001-057 Program –"Self-powered body sensor network for disease management and prevention-oriented healthcare "under R-263-000-A27-281 from National Research Foundation (NRF), Singapore.

References

[1] W. den Boer, A. Abileah, P. Green, T. Larsson, S. Robinson, T. Nguyen, Active matrix LCD with integrated optical touch screen, in: SID Symposium Digest of Technical Papers, vol. 34, 2003, pp. 1494–1497.

[2] G.J.A. Destura, J.T.M. Osenga, S.J. van der Hoef, A.D. Pearson, Novel touch sensitive in-cell AMLCD, in: SID Symposium Digest of Technical Papers, vol. 35, 2004, pp. 22–23.

[3] H. Hayashi, T. Nakamura, N. Tada, T. Imai, M. Yoshida, H. Nakamura, Optical sensor embedded input display usable under high-ambient-light conditions, in: SID Symposium Digest of Technical Papers, vol. 38, 2007, pp. 1105–1108.

[4] H.S. Lim, O.K. Kwon, Ambient light sensing circuit with low-temperature polycrystalline silicon p-intrinsic-n diode and source follower for auto brightness control, Japanese Journal of Applied Physics 47 (2008) 1919–1923.

[5] B.H. You, B.J. Lee, S.Y. Han, S. Takahashi, B.H. Berkeley, N.D. Kim, S.S. Kim, Touch-screen panel integrated into 12.1-in. a-Si:H TFT-LCD, Journal of the Society for Information Display 17 (2009) 87–94.

[6] C.S. Kim, B.K. Kang, J.H. Jung, M.J. Lee, H.B. Kim, S.S. Oh, S.H. Jang, H.J. Lee, H. Kastuyoshi, J.K. Shin, Active matrix touch sensor perceiving liquid crystal capacitance with amorphous silicon thin film transistors, Japanese Journal of Applied Physics 49 (2010), 03CC03.

[7] C. Wang, P. Ramanathan, K.K. Saluja, Calibrating nonlinear mobile sensors, in: IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 2008, pp. 533–541.

[8] N.J. Cotton, B.M. Wilamowski, Compensation of sensors nonlinearity with neural networks, in: IEEE International Conference on Advanced Information Networking and Applications, 2010, pp. 1210–1217.
[9] J.H. Kang, E. Um, J.K. Park, Fabrication of a poly(dimethylsiloxane) membrane with well-defined through-holes for three-dimensional microfluidic networks, Journal of Micromechanics and Microengineering 19 (2009) 045027.
[10] J.D. Zahn, Method in Bioengineering: Biomicrofabrication and Biomicrofluidics, Artech House, London, 2010.
[11] P.G. De Gennes, J. Prost, The Physics of Liquid Crystals, 2nd ed., Clarendon Press, Oxford, 1993.
[12] J. Feng, Y. Zhao, S.S. Li, X.W. Lin, F. Xu, Y.Q. Lu, Fiber-optic pressure sensor based on tunable liquid crystal technology, IEEE Photonics Journal 2 (2010) 292–298.
[13] Y.T. Lai, Y.M. Chen, T. Liu, Y.J. Yang, A tactile sensing array with tunable sensing ranges using liquid crystal and carbon nanotubes composites, Sensors and Actuators A: Physica 177 (2012) 48–53.
[14] D.S. Gray, J. Tien, C.S. Chen, Repositioning of cells by mechanotaxis on surfaces with micropatterned Young's modulus, Journal of Biomedical Materials Research Part A 66 (2003) 605–614.
[15] X. Nie, H. Xianyu, R. Lu, T.X. Wu, S.T. Wu, Pretilt angle effects on liquid crystal response time, Journal of Display Technology 3 (2007) 280–283.
[16] M.Y. Cheng, C.L. Lin, Y.T. Lai, Y.J. Yang, A polymer-based capacitive sensing array for normal and shear force measurement, Sensors 10 (2010) 10211–10225.

Biographies

Chia-Yi Huang received his Ph.D. degree from Institute of Electro-Optical Science and Engineering, National Cheng Kung University, Taiwan, in 2010. He is currently a postdoctoral research fellow in Department of Electrical & Computer Engineering, National University of Singapore, Singapore. His research interests include MEMS, liquid crystal-based photonic devices and attenuated total reflection system.

Liang Lou received his B.Eng. degree from the Department of Electronic Engineering and Information Science, University of Science and Technology of China, China, in 2008. He has received his Ph.D. from Department of Electrical & Computer Engineering at National University of Singapore in 2012, Singapore. He is a senior research engineer at Institute of Microelectronics (IME), A-STAR, Singapore.

Aaron J. Danner is an Assistant Professor at the National University of Singapore where his research group focuses on solar cells, photonic crystals, metamaterials, and gradient index optics. Prior to his appointment to NUS, he was employed at Agilent (now Avago) Technologies, where he worked on vertical cavity lasers and LEDs. He received his B.S. degree in Electrical Engineering from the University of Missouri-Columbia and completed his Ph.D. in Electrical Engineering from the University of Illinois at Urbana-Champaign in 2005. He is a fellow of the U.S. National Science Foundation and a member of the IEEE-Lasers and Electro-Optics Society (LEOS) and the Optical Society of America (OSA).

Chengkuo Lee received the M.S. degree in materials science and engineering from National TsingHua University, Hsinchu, Taiwan, in 1991, the M.S. degree in industrial and system engineering from Rutgers University, New Brunswick, NJ, in 1993, and the Ph.D. degree in precision engineering from The University of Tokyo, Tokyo, Japan, in 1996. He worked as a foreign researcher in the Nanometerscale Manufacturing Science Laboratory of the Research Center for Advanced Science and Technology, The University of Tokyo, from 1993 to 1996. He had also worked in the Mechanical Engineering Laboratory, AIST, MITI of Japan as a JST Research Fellow in 1996. Thereafter, he became a senior research staff member of the Microsystems Laboratory, Industrial Technology Research Institute, Hsinchu, Taiwan. In September 1997, he joined Metrodyne Microsystem Corporation, Hsinchu, Taiwan, and established the MEMS device division and the first micromachining fab for commercial purposes in Taiwan. He was the manager of the MEMS device division between 1997 and 2000. He was an adjunct assistant professor in the Electro-physics Department of National Chiao Tung University, Hsinchu, Taiwan, in 1998, and an adjunct assistant professor in the Institute of Precision Engineering of National Chung Hsing University, Taichung, Taiwan, from 2001 to 2005. In August 2001, he cofounded Asia Pacific Microsystems, Inc. (APM), where he first became vice president of R&D, before becoming vice president of the optical communication business unit and special assistant to the Chief Executive Officer in charge of international business and technical marketing for the MEMS foundry service. From 2006 to 2009, he was a senior member of the Technical Staff at the Institute of Microelectronics, A-Star, Singapore. He has been an assistant professor in the Department of Electrical and Computer Engineering, National University of Singapore, Singapore, since December 2005. He is the coauthor of Advanced MEMS Packaging (McGraw-Hill, 2010). He has contributed to more than 160 international conference papers and extended abstracts and 120 peer-reviewed international journal articles in the fields of Sensors, Actuators, Energy Harvesting, MEMS, NEMS, nanophotonics, and nanotechnology. He is also the holder of nine U.S. patents.