

PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Millimetre-wave beam steering with analog-resolution and minimised distortion based on liquid crystals tunable delay lines with enhanced signal-to-noise ratios

Li, Jinfeng

Jinfeng Li, "Millimetre-wave beam steering with analog-resolution and minimised distortion based on liquid crystals tunable delay lines with enhanced signal-to-noise ratios," Proc. SPIE 11541, Millimetre Wave and Terahertz Sensors and Technology XIII, 115410H (20 September 2020); doi: 10.1117/12.2570001

SPIE.

Event: SPIE Security + Defence, 2020, Online Only

Millimetre-wave beam steering with analog-resolution and minimised distortion based on liquid crystals tunable delay lines with enhanced signal-to-noise ratios

Jinfeng Li^{*a,b}

^aCentre for Electronics Frontiers, Zepler Institute for Photonics and Nanoelectronics, University of Southampton, Southampton SO17 1BJ, United Kingdom; ^bDepartment of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, United Kingdom

ABSTRACT

Millimetre-wave beam-steering distortions are due mainly to unbalanced feeding amplitudes among the delay lines network. To compensate for this, active amplifiers or attenuators are employed, increasing the circuit complexity and costs, whilst compromising the passive array advantage. This work presents a passive millimetre-wave distortion-free beam steering solution with analog resolution in liquid crystal planar delay line technology. Enclosed coplanar waveguide (ECPW) tunable delay lines with 0-180° and 0-360° phase-shifting ranges are prototyped respectively. A novel impedance matching and mismatching approach for amplitude compensation is proposed and verified, as evidenced by the 67 GHz measured maximum insertion loss of -4.37 dB (variation up to 5%) for the 0-180° delay line, and -8.28 dB (variation up to 8%) for the 0-360° device. Based on a smart combination of the 0-180° and 0-360° ECPW, an optimised delay lines deployment scheme is proposed for two-dimensional beam steering with a fault tolerance capability and a minimised systematic insertion loss in total on the feeding network.

Keywords: electronic beamforming, liquid crystal, millimetre wave, phased array radar, phase shifter, super-resolution, true time delay line, ultra-wideband.

1. INTRODUCTION

Millimetre-wave (mm-wave) beam steering desires ultra-fine scanning resolutions for applications in high-resolution imaging [1] as well as uninterrupted communication between antennas in a constantly varying environment [2, 3]. Key technology to realise this is through precise delays of the mm-wave signal at each antenna array element. Current status of mm-wave phased array exhibits limited steering resolutions, due mainly to the digital nature of switches-based phase shifters as illustrated in Figure 1. Such switch-based delay lines have been implemented in different ways, such as GaAs or GaN based p-i-n diodes [4] and Schottky diodes [5]. The phase-shift resolution is limited by control bits, i.e. the number of transmission lines to be switched, e.g. a 4-bit digital delay line delivers a resolution of only 22.5°. Furthermore, solid-state delay lines based on GaAs monolithic microwave integrated circuit (MMIC) exhibit unacceptably high losses [6] due to high dissipation factors of the materials in the mm-wave band. Ongoing innovations in tunable dielectrics such as liquid crystals (LC) have enabled continuously variable delay lines in theory, but practical resolution is significantly degraded by noises [2]. More fundamentally, higher-order modes, surface-wave radiation, impedance mismatch, and amplitude unbalancing [7] challenge the delay lines rollout for wideband fine-resolution mm-wave beam steering. By way of illustration, Figure 2 (a) outlines the principle of liquid crystals tuning based on dielectric anisotropy, producing dipole moments that align themselves in the direction of the low-frequency bias voltage. A classical structure of two-planar-electrodes is sketched, separated by a distance (cell gap) where LC and alignment layers are placed. The cell gap is within the range of the anchoring effect enforced by surface treatment (alignment layer). Figure 2 (b) points out the unequal potential problem occurring at mm-wave for the conventional coplanar waveguide (CPW) structure with floating electrodes, which limits their operation bandwidths because of the propagation of multiple undesirable modes (e.g. slot line mode, parallel plate mode and waveguide mode).

*Jinfeng.Li@soton.ac.uk; ORCID iD: 0000-0001-9462-2625

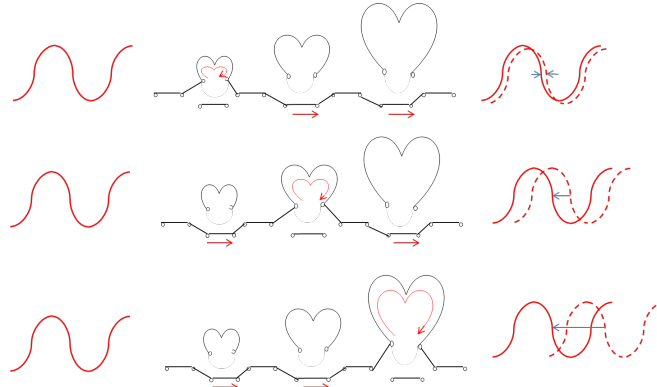


Figure 1. Principle of conventional mm-wave multi-switchable delay lines with phase shifts of 45° , 90° , 180° respectively

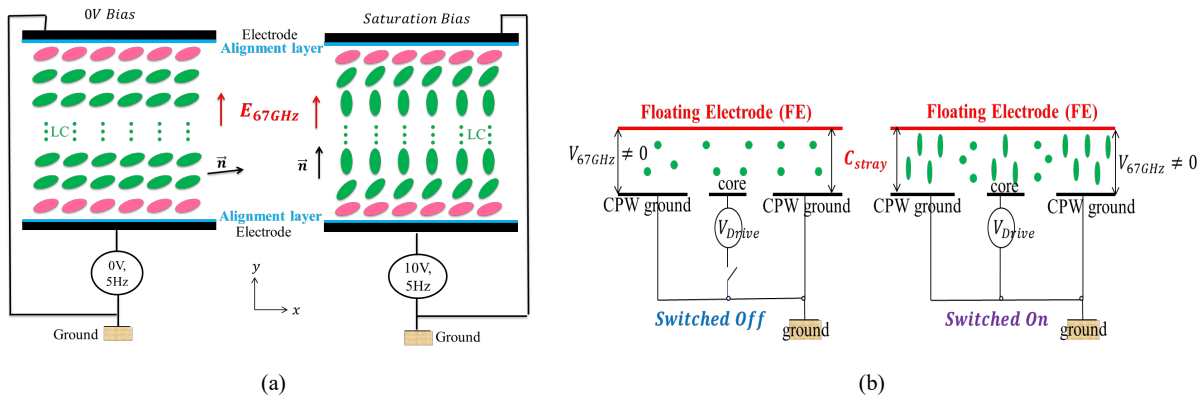


Figure 2. (a) Tuning mechanism of LC delay line (b) traditional CPW with parasitic modes due to floating electrodes

2. LOW-NOISE DISTORTION-FREE DELAY LINES DESIGN

2.1 Noises and higher-order modes screening

To tackle the stray modes and noises, we design and demonstrate LC-based ultra-wideband true-analog 0 - 180° and 0 - 360° true-time-delay phase shifters driven by a 0 - 10 V bias. The delay lines are designed in a stray-modes-free enclosed coplanar waveguide (ECPW) structure for 1 - 67 GHz. Featuring a semi-shielded enclosure electrically bonding the coplanar grounds, the proposed ECPW layout and biasing scenario are depicted in Figure 3.

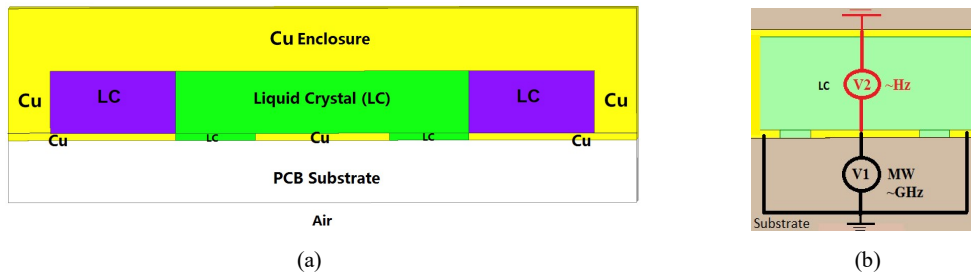


Figure 3. Cross section sketch of (a) proposed ECPW structure (b) electrical biasing scheme

The chief advantage of the structure lies in the enhanced signal-to-noise ratios due to the elimination of unstable floating electrodes without using lossy bond wires or complex vias, while allowing the use of well-established planar PCB and LC microwave technology [8, 9]. In addition to the novelty of the ECPW configuration for screening out noises, a few new approaches are incorporated to enable the mm-wave phased array with enhanced performance, e.g. a smart impedance-matching scheme for balancing the output signals' amplitude and minimising beam-steering distortions.

2.2 Amplitudes balancing of phase-shifted signals

Phase array beam steering requires not only a precise phase shift feeding each radiating element, but also the correct amplitude of the feeding signal, for which the insertion loss of each delay line matters. Note that the insertion loss can be decomposed into material loss (absorptions in conductors and dielectrics), radiation loss, as well as reflection loss due to impedance mismatch. For the highly shielded ECPW, radiation loss is not a big deal, and hence what we can play with are mainly the material absorption and return loss. In different phase-delaying states between 0 and π (or 0 and 2π), the characteristic impedance and return loss could vary remarkably with the bias voltage due to the dielectric anisotropy of the LC. At the bias where the mm-wave polarisation is perpendicular to the LC director field, LC's molecular absorption is at a maximum. As evidenced by a highly anisotropic LC (GT3-24002) used in this work, the perpendicular state exhibits a dissipation factor of 0.0123, as contrast with 0.0032 at a parallel state. The contrast in the dielectric dissipation factor results in unignorable insertion loss imbalance (deviation can reach a few dB) among different tuning states, notably between the perpendicular state against the parallel state, which leads to undesirable beam scanning distortions.

To unleash the possibility of insertion loss balancing, we leverage the impact of LC's dielectric anisotropy on characteristic impedance and thus tailor the return loss for amplitude compensation without additional amplifiers or attenuators. The method is implemented by designing the ECPW geometry to perfectly matched ($50\ \Omega$) at the LC's largest absorption loss state (i.e. perpendicular), while less matched at other biasing states, and least matched at the LC's smallest absorption state (i.e. parallel). In this way, the increased LC absorption is cancelled out by a lower return loss, the reduced LC absorption is compensated by a higher return loss, hence resulting in a largely balanced insertion loss amplitude profile for minimised steering distortions.

3. DELAY LINES ASSEMBLY AND MEASUREMENT RESULTS

Two designs of different phase shifting ranges (0-180°, and 0-360°, differing only in the line length) are fabricated following the procedures and methods as detailed in Table 1.

Table 1. Fabrication and assembly process of the LC mm-wave tunable delay lines

Procedures	Material specifications	Fabrication methods
PCB engraving	1.575mm-thick RT/duroid 5880	Photolithography
Enclosure machining	Pure Cu plates (grade: C101)	Electrical discharge machining
Gold plating	2 μ m gold on Cu, nickel-free	Standard electrolytic process
Planar alignment	AL1254 polyimide (JSR Optmer)	Spin coating and roller rubbing
Substrates mounting	Screws and silver conductive paste	Mechanical mounting and conductive paste bonding
LC filling	GT3-24002 LC (clearing at 175°C)	Heating to clearing temperature, then capillary action
Device packaging	Glue and ultraviolet (UV) lamp	Glue line writing, then UV curing
Connectors install	Edge-mount end-launch connectors	Interference fit without soldering

Figure 4 presents images of the fabricated delay line device optimised after iterations of designs and testing. The insertion loss and differential phase shift performance are measured by a vector network analyser (VNA) and plotted against each other at 67 GHz as summarised in Figure 5. The 0-180° delay line exhibits a maximum insertion loss of -

4.37 dB (0V bias, 0° shift state), with a variation only up to 5% for other shifting states. The 0-360° delay line exhibits -8.28 dB and a maximum variation level of 8%.

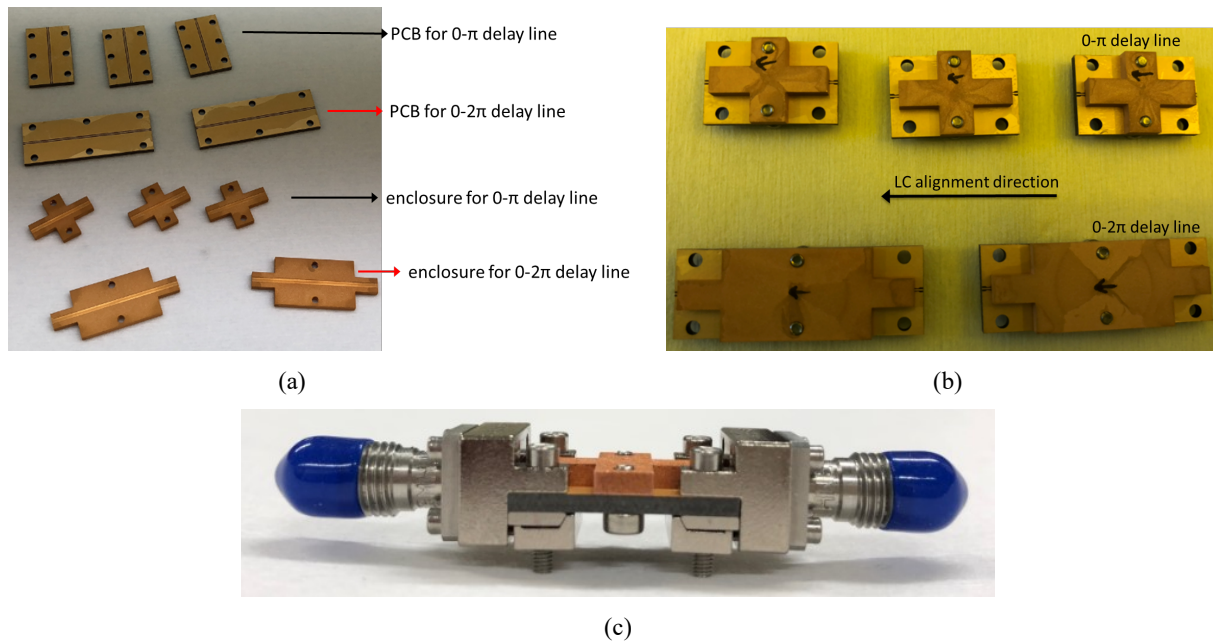


Figure 4. (a) Processed substrates of different sizes before assembled (b) assembled delay lines with alignment and filled with LC (c) whole device of a 0-180° delay line prototype packaged with connectors

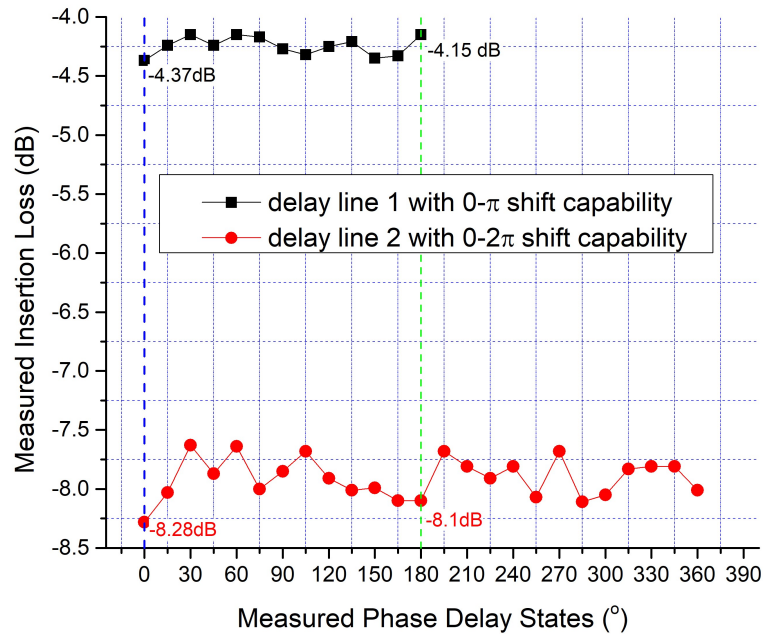


Figure 5. Measured insertion loss at different phase-delaying states for 67 GHz

4. DISCUSSION ON DELAY LINES DEPLOYMENT FOR BEAM STEERING

The developed LC-based ECPW delay lines are scoped for integration into a phased array antenna (Figure 6) as a non-mechanical millimetre-wave beam steerer with lightweight and a small footprint. To do this accurately and efficiently, 67 GHz beams can be steered electronically by sequentially shifting the phase of each radiating components (realised by tuning the proposed LC-based ECPW delay lines) to produce constructive or destructive interference for shaping the desired radiation pattern. For instance, tilting the main lobe of a linear array antenna consisting of equally spaced elements can be realised by controlling the voltage bias to each unit (0-10 V), with each pixel excited by a LC-based ECPW delay line. With emitters fed by the proposed high-performance delay lines, a linearly increasing phase progression profile could be produced, allowing individual wave fronts to propagate diverse distances at a given time. The cumulative wave front is thereby tilted by a pivot angle, and thus all the elements radiate coherently along a desired direction.

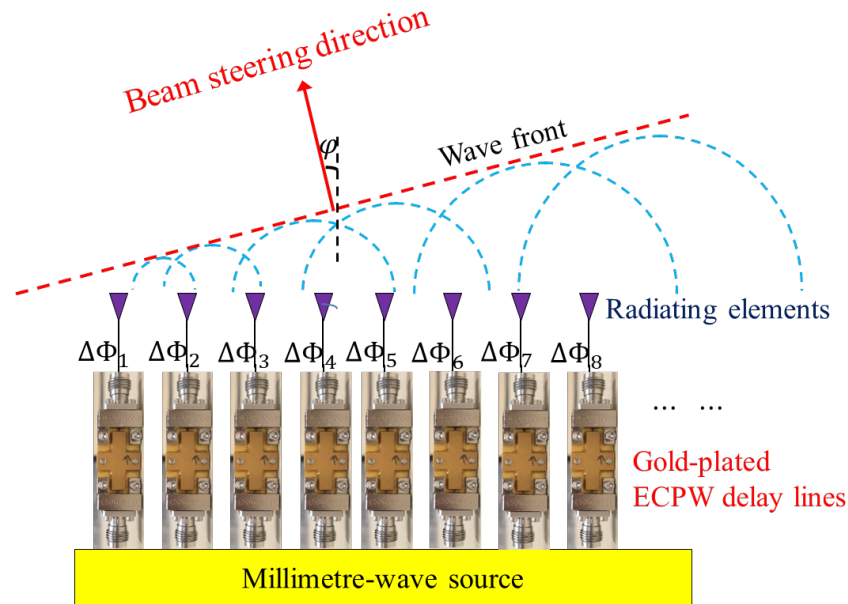


Figure 6. An 8-element electronically steered phased array fed by proposed delay lines

An optimised scenario of delay lines deployment for the beam steering is derived based on the measured performance matrix of phase shift, insertion loss, and bias voltage for the 0-180° delay line design and the 0-360° one. For a required phase shift range below 180°, using the 0-180° delay line design obtains a lower insertion loss due to a shorter line length (corresponding to metal loss) and smaller LC volume (corresponding to dielectric loss) than that of the 0-360° design. For instance, for the targeted phase shift state of 180° at 67 GHz, the 0-180° device (fixed length of 1.72 cm) operates under a bias of 10 V, while the 0-360° device (length of 3.44 cm) operates under a lower bias 6.7 V. Note that LC molecules biased with a lower voltage exhibits a larger dissipation factor, i.e. $\tan\delta(6.7\text{ V}) > \tan\delta(10\text{ V})$. Thereby, the longer line length (with degraded substrate uniformness) and the larger dissipation factor jointly results in an increased insertion loss by 3.95 dB when comparing the 0-360° design (-8.1 dB) with the 0-180° one (-4.15 dB) at the 180° phase-shifting state.

As a consequence, we obtain a flexible and modular delay lines deployment scheme for beam steering with a smart combination of shorter (0-180°) and longer (0-360°) delay lines (both continuously tuned). More shifting designs (e.g. 0-90°, 0-120°, 0-270°) could be deployed in the feeding system, depending on the number of radiating elements and the beam scanning requirement. Additionally, fault tolerance is achieved, since the 0-360° device can substitute the 0-180° one, and vice versa. Last but not least, though the low-loss device performance is verified currently up to 67 GHz (due to the measurable frequency range of the VNA), we can envisage the devices scalable from 70 GHz to 90 GHz

targeting extended applications. Bandwidth limitation of the ECPW lies mainly in the enclosure's cavity width (as compared with a half of the guided wavelength), which defines the highest frequency before the onset of higher-order waveguide modes coming into play.

5. CONCLUSION

This work pioneers the LC-based mm-wave beam steering technology with four main advances, i.e. the $0-2\pi$ continuous phase shift for unlimited beam steering resolution, the true-time-delay nature (group delay independence on frequency) for beam squinting-free performance, linear phase shift-voltage response, and standalone amplitude balancing solution without additional bulky compensation networks. Delay lines with both $0-180^\circ$ and $0-360^\circ$ shifting ranges are prototyped for two-dimensional beam steering, with the measured maximum insertion loss of each element at 67 GHz as -4.37 dB and -8.28 dB, respectively. The variations in the insertion loss amplitude are only up to 5% and 8%, respectively, hence verifying the minimisation of the beam-steering distortion. The modular hardware solution complements complex beam-forming algorithms and helps alleviating computation burden in back-end real-time signal processing for massively high data rates. Scalability towards 90 GHz is discussed for future development. Compared with state-of-the-art ferroelectric [10] and left-handed [11] phase shifters with digital resolutions, the optimised LC delay lines demonstrated in this work exhibit enhanced signal-to-noise ratios, analog resolution, and ease of control, which are highly desirable for integration into electronically steerable phased array antenna targeted mm-wave radar-based sensing, imaging, weather observation, aircraft surveillance, and homeland defence applications.

ACKNOWLEDGEMENT

The author acknowledges the training from Centre for Photonic Devices and Sensors, University of Cambridge. The author would like to thank the supports from Imperial College London and University of Southampton.

REFERENCES

- [1] Meng, Y., Qing, A. Y., Lin, C., Zang, J. F., Zhao, Y. Z. and Zhang, C., "Passive Millimeter Wave Imaging System Based on Helical Scanning," *Sci Rep* 8, 7852 (2018).
- [2] Cai, L. G., Xu, H., Li, J. F. and Chu, D. P., "High FoM liquid crystal based microstrip phase shifter for phased array antennas," in 2016 International Symposium on Antennas and Propagation (ISAP), Okinawa, 2016, pp. 402–403.
- [3] Li, J. F. and Chu, D. P., "Liquid crystal-based enclosed coplanar waveguide phase shifter for 54–66 GHz applications," *Crystals*, vol. 9, 12, 650, December 2019.
- [4] Kamoda, H., Iwasaki, T., Tsumochi, J. and Kuki, T., "60-GHz electrically reconfigurable reflectarray using p-i-n diode," 2009 IEEE MTT-S International Microwave Symposium Digest, Boston, MA, 2009, pp. 1177–1180.
- [5] Sankaran, S. and K. K. O., "Schottky barrier diodes for millimeter wave detection in a foundry CMOS process," in *IEEE Electron Device Letters*, vol. 26, no. 7, July 2005, pp. 492–494.
- [6] Gunnarsson, S. E. et al., "Single-Chip 60 GHz Transmitter and Receiver MMICs in a GaAs mHEMT Technology," 2006 IEEE MTT-S International Microwave Symposium Digest, San Francisco, CA, 2006, pp. 801–804.
- [7] Li, J. F., "All-optically Controlled Microwave Analog Phase Shifter with Insertion Losses Balancing," *Engineering Letters*, vol. 28, no. 3, pp. 663–667, 2020.
- [8] Yontem, A. O., Li, J. F. and Chu, D. P., "Imaging through a projection screen using bi-stable switchable diffusive photon sieves," *Opt. Express*, vol. 26, pp. 10162–10170, April 2018.
- [9] Li, J. F., "Low-loss tunable dielectrics for millimeter-wave phase shifter: from material modelling to device prototyping," *IOP Conference Series: Materials Science and Engineering*, vol. 892, 012057, 2020.
- [10] Vélú, G., Burgnies, L., Houzet, G., Blary, K., Lippens, D. and Carru, J. C., "Characterization of Ferroelectric Films up To 60 GHz: Application to Phase Shifters," *Integrated Ferroelectrics*, vol. 93, 1, pp. 110–118, 2007.
- [11] Kumar, P. P. and Saxena, P., "Design and Analysis of 20–60 GHz Broadband Left-Handed Metamaterial," 2020 National Conference on Communications (NCC), Kharagpur, India, 2020, pp. 1–5.