Digital Twinning Transformation for Microwave Engineering Education: A Case Study of Student-centered Learning in Module States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G

Jinfeng Li, *Member, IAENG* and Haorong Li

***Abstract*—The pervasive use of electronic design automation (EDA) suites is not solely dedicated to state-of-the-art microchips and nanosheet devices designed for Interconnect 3.0, but is also extensively deployed for more macroscopic electromagnetic analysis that profoundly influences the fifth-generation (5G) communications underway and beyond, e.g., the sixth-generation (6G) one that fuses communication and sensing in a highly integrated manner and featuring ubiquitous connectivity. High-frequency structure simulator (HFSS) is one of the most prominent EDA tools in this domain, but due to its closed-source nature, its value in engineering education and student-centered learning has largely been underexplored. To this end, this study investigates the use of EDA-assisted electromagnetic (EM) simulation tools, focusing on emerging liquid crystal (LC)-based microwave (MW) reconfigurable technologies, in the context of teaching an undergraduate module titled States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G. Eleven in-project undergraduate students across diverse academic backgrounds participated in the case study, together with the lecture and a postgraduate research student. The novelty of this approach lies in its development of a self-driven framework to identify and address the limitations of these computational tools in various application scenarios. These educational innovations form a core part of the broader reform project carried out at Beijing Institute of Technology, aimed at integrating digital twinning and digital transformation strategies into higher education. Marrying EDA vulnerability studies with LC-based computational electromagnetics offers an extended educational pathway toward 6G technologies and opens new opportunities in liquid crystal microwave technology and beyond.**

***Index Terms*—microwave engineering, digital twin, engineering education, computational electromagnetics, liquid crystal education, digital transformation, student-centered learning, higher education, 6G education, 6G networks**

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I. INTRODUCTION

As liquid crystal (LC) materials [1–3] and their derivation of passive tunable-dielectrics-enabling reconfigurable technologies [4–7] evolve rapidly for 5G (fifth-generation wireless communication) components [8], devices [9], sub-systems [10], and networks [11], the transition underway from the conventionally binary-resolution switching paradigm dominated by solid-state semiconductor switches [12–14], towards the post-5G networks (e.g., 6G envisaged to take place by 2030 [15]), has sparked significant innovation in both academic and industrial sectors, wherein the dynamic manipulation of electromagnetic (EM) waves (more specially, the wavefront phase and/or amplitude control) [16] is of fundamental importance to electronic beam steering (EBS) [17][18], an energy-efficient means of controlling the EM radiation to combat the high-frequency-induced elevated propagation loss [19], by varying the main lobe (shape and direction of the main beam) dynamically.

While there has been a host of up-to-date whitepapers [20–22] and technical articles [23–25] documented for the dedicated states-of-the-arts in EBS devices and systems (in particular, phased array antennas [26], metamaterials [27–29], and metasurfaces [30]) in the recent decade prior to the launch of 6G, scarcity of study investigates the engineering education upgrade involving these newly emerged developments that underpin the next phase of telecommunication and may redefine the standard of next-generation information processing.

While the traditional EBS has been lectured and showcased (animated) in a host of undergraduate and postgraduate lecturers on microwave (MW) engineering offered by substantial institutes and universities, e.g., Massachusetts Institute of Technology (MIT) [17], and Imperial College (IC) [18], so far, there is unfortunately a significant lack of tailored higher-education engineering modules on the newly emerged subject matter concerning the unconventional devices and ecosystems leveraging liquid crystal MW technology for EBS targeting the 6G roadmap. This gap is illustrated in Fig. 1.

Recapitulating the last decade of new developments in industry and academics that impact the evolution of MW engineering education, internet-of-things (IoT) [31] was arguably one of the key new paradigms at the transition from 4G [32][33] to 5G. For now, in 2025, standing at the crossroad toward 6G (anticipated to take off in 2030) AGI (Artificial General Intelligence) and AIoT (Artificial Internet of Things), the next standard-defining technology of reconfigurability should be put on the agenda that inspires the next generation of MW practitioners (including but not limited to MW engineers, university academics, lab technicians, students, amateur radio operators, and open-source hardware enthusiasts) to advance radio communication and technical skills.

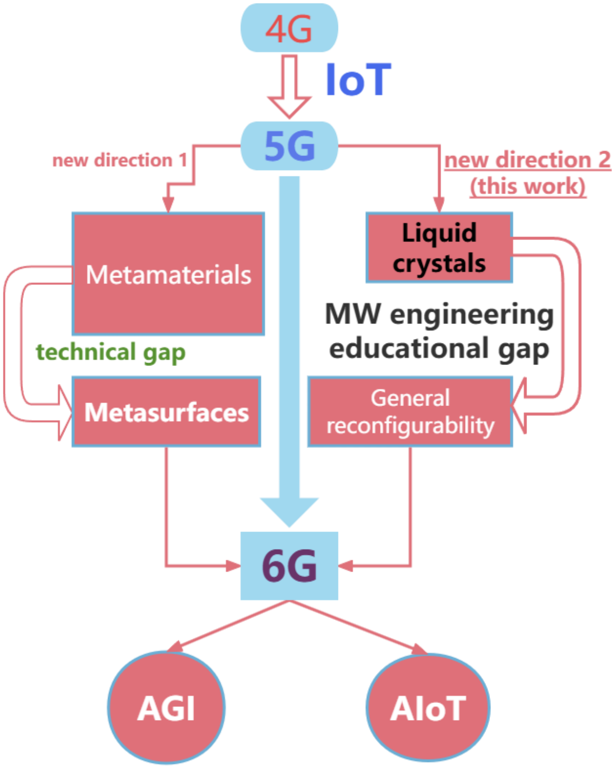

Fig. 1. Rethinking microwave (MW) engineering educational gaps and ever-expanding opportunities at the intersection of 5G towards 6G wireless communication networks.

Fortunately, at the Beijing Institute of Technology (BIT), these challenges prompted the launch of a new undergraduate elective course in early 2024, titled States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G. Selectable for undergraduate students from Year 1 to Year 3, this 3-month course aims to bridge the gap between cutting-edge research in LC-based MW technologies [23][24] and undergraduate education, incorporating EDA simulation tools like MATLAB and HFSS (high-frequency structure simulator) [34][35] into both lecture and lab formats. By integrating digital twinning strategies [36] into the curriculum, the module offers a dynamic and interactive learning environment where students can practice spotting the vulnerabilities of EDA tools whilst gaining a deeper understanding of the principles behind LC MW technology. The classroom instruction is offered on a weekly basis, lasting for 11 weeks in an academic term.

The case study reported in this paper elaborates on this course from the establishment to the successful ending of the first term (see Fig. 2 for the end-of-term group photo involving the lecturer and students who participated in this case study from early 2024 to early 2025).

Fig. 2. End-of-term group photo for participants of the case study, i.e., the teacher and 11 in-project students of the course entitled States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G (photograph taken on 28 May 2024 at Beijing Institute of Technology, Beijing, China).

This semi-technical, semi-explorative work discusses the design and implementation of this innovative educational approach for MW engineering and the strides made in understanding how digital twinning-targeted digital transformation can be seamlessly blended into higher education to enhance teaching and student-centered learning in 6G-related technologies. Specifically, it explores the challenges of MW teaching, the role of simulation tools, and the benefits of a hands-on, vulnerability-driven approach to enhance the learner's involvement. The outcomes of the student-centered learning are continuously monitored and critically assessed to inspire new understanding (e.g., observations of new vulnerabilities in using EDA for developing LC MW devices) that benefit a wider engineering community.

For ease of understanding the logic and flow of our work, this paper is structured in the following parts. Part II reviews the conventions of MW education, identifying the key drawbacks and challenges that impede the prosperity of the subject. Digital transformation and EDA-assisted EM simulation tools are proposed as a promising solution for the cost-risk dilemma. Part III incorporates this newly conceptualized framework into the educational delivery of the LC MW module (i.e., States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G) held weekly on Tuesdays. The outcomes of the students' hands-on simulations give rise to four new topics under discussion for degrading the performance of LC MW devices, as analyzed in Part IV, concerning the notch frequency drifting for tunable filtering applications, susceptibilities of line-length parameterization in differential phase shift prediction, per-line-length parameterization for figure-of-merit (FoM) estimation, and the fully-enclosed boundary condition that imply the device packaging technique.

II. STATUS OF MICROWAVE ENGINEERING EDUCATION

Modern engineering education and practice face transformative challenges that demand innovative approaches. Section A in this chapter rethinks the conventions of teacher-focused learning, advocating for student-centered, experiential models that bridge theory and real-world application. Section B examines the cost, risk, and universal complexity of modern engineering problems, which increasingly span multiple physics domains and scales—posing unprecedented challenges for traditional methodologies. Finally, Section C introduces digital twinning and in-project campaigns as dynamic solutions, enabling real-time simulation, iterative learning, and collaborative problem-solving in engineering education and practice. Together, these sections explore how evolving pedagogical and technological strategies can prepare future engineers for an increasingly intricate and interconnected world.

A. Rethinking the Conventions of Teacher-focused Learning

First, in the initial phase of this module teaching, the general phase shifting principle [37], materials (conductors and tunable dielectric, i.e., LC) [38], and the wave-guiding device architecture (coaxial [39] for instance) involved, were graphically illustrated to the students, combining the conventional handwriting and the multi-media teaching approaches. Rain Classroom (an online software on the cloud) is leveraged for statistics recording (including attendance and multi-choice questions).

The key topic can be boiled down to the transmission line effect analysis, which is arguably a signature dish for the appetite of students from a plethora of backgrounds (electronic, electrical, mechanical, chemical, physics, and materials, along with many others). For MW engineering, this is arguably the must-taught element.

Microwave engineering education faces several challenges at both the undergraduate and graduate levels. Traditional teaching methods, which rely heavily on in-class lectures and controlled lab experiments, often struggle to keep pace with the rapid advancements in 6G technologies. Additionally, these methods tend to focus on established industry standards (become increasingly constrained nowadays), such as the widely accepted 50 Ω impedance for transmission lines, without encouraging students to question or challenge these norms.

B. Cost, Risk, and Universal Challenge of Multi-physics Multi-scale Nature of Modern Engineering Problems

One of the key obstacles in MW education is the cost and risk associated with hands-on experimentation. High-end MW equipment like vector network analyzers and waveguide components are expensive and fragile, limiting their use in undergraduate courses. Edging towards even higher frequencies, the instrumentation of photonics-based systems requires extensive alignment and time-consuming calibration for reliable characterization of materials and devices. However, undergraduate students often lack the opportunity to engage in iterative, trial-and-error learning due to time and resource constraints. This hampers their ability to develop critical problem-solving skills and limits their exposure to the complexities of modern MW devices, an intricate interplay between theory and practice concerning device physics and chemistry, material sciences and synthesis, component packaging and volume production, system complexity and fault tolerance, and more aspects to be discussed and inspiring future rethinking.

More fundamentally, a universal challenge for both MW designers and academics is the multi-physics, multi-scale nature of functional MW devices and systems. By way of illustration, in the time or frequency domain, the LC MW devices arguably encompass mixed-signal circuits blending a low-frequency (e.g., in Hz or kHz) driving signal and a high-frequency (e.g., in GHz) transmitted signal, i.e., of diverse purposes but embedded in one device. Notably, the wavelengths of these two signals can vary over several orders of magnitude, indicating the multi-scale nature of the problem (from the time or frequency domain to the space domain), as illustrated in Fig. 3 below.

Other multi-scale problems are embedded in the geometry that accommodates the functional materials, e.g., the nanoscale molecules of LC are accommodated by the cavity with a cross-sectional size in millimeter-scale (core line width and the spacing between conductors). Suitable tradeoffs and considerations should be placed on the geometry design (e.g., which transmission line structure to deploy to accommodate the LC) for various purposes (priorities), e.g., for the integration with a 4G/5G cellular antenna (operating from MHz to GHz, e.g., from the low-band spectrum 400 MHz to the 6 GHz for the sub-6 GHz operation of 5G), the broadband and the resultant scales ranging from cm to mm for different elements (e.g., axial length, cross sections can differ in scales over an order of magnitude) shall be anticipated by the students.

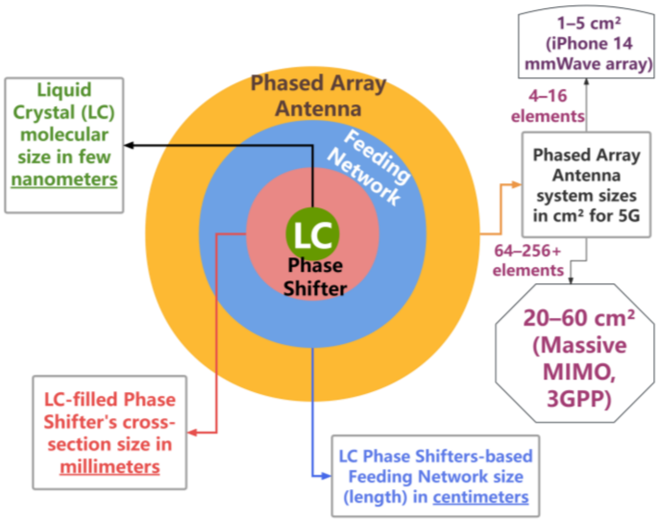

Fig. 3. Multi-scale (from nanometers to centimeters), multi-physics nature behind LC MW components, devices, feeding network sub-systems, and phased array antenna systems concerning electromagnetic and electromechanical couplings among various subjects in various scales.

C. Digital Twinning Solution and In-project Campaigns

To address these issues and de-risk the costly experimentation, digital twinning and digital transformation offer a promising alternative. By shifting the functionality of physical devices into a virtual environment, students can engage in realistic, low-risk computational simulations that mimic the behavior of actual MW components. This approach not only reduces the cost and risk of experimentation but also enables students to explore new ideas, identify design flaws, and propose innovative solutions without fear of damaging expensive equipment.

Despite transformations of in-class lecturing (and hands-on lab experimentation) as a formal MW engineering education format, newer approaches leveraging unconventional digital transformation are urgently needed for engaging students to learn how to strike a balance in lectures, labs, supervisions, and outreach. To back up the claim, we subsequently carried out in-class experiments and in-project campaigns, collating submissions of vulnerabilities spotted during the usage of EDA-assisted EM simulation tools from students.

The potential benefits of this practice of entertaining simulation experiments are more than getting the students' hands dirty without worrying about the damage of the costly instrument (e.g., vector network analyzers); they extend into an overarching goal of win-win-win achieved among the teaching party, the lab, and the students. Furthermore, a few fundamental yet significantly alerting drawbacks (risk-posing unstable operations) were collated to inform the digital twinning of LC-combined reconfigurable MW devices (e.g., phase shifters) embedded in a phased array antenna system for the 5G and 6G eras. Implicitly, this pro-active digital transformation approach also targets to distil the LC-based reconfigurable MW devices research into accessible formats for generalist audiences, particularly, in the hope that it will motivate students from disadvantaged backgrounds (e.g., not technical) who couldn't be bothered to challenge their status quo by attempting the LC MW device design in a trial-and-error manner.

III. Digital Twinning in Teaching LC-based Microwave Configurable Technology

Liquid crystal-based microwave (LC MW) technology represents a particularly fruitful area for the potential implementation of digital twinning strategies. LC materials, with their electronically tunable dielectric properties, offer great potential for use in reconfigurable MW devices, e.g., phase shifters [40], filters [41], and antennas [42]. However, designing and optimizing these devices requires a deep understanding of the underlying electromagnetic (EM) principles and the ability to model complex interactions [43] between LC materials and EM fields.

In the States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G course, students are introduced to the principles of LC MW device design through a combination of lectures, hands-on labs, and EDA-assisted simulations. HFSS, a widely used EDA tool, plays a central role in these simulations, allowing students to visualize how changes in device geometry and material properties affect EM performance.

The digital twinning component of the course is designed to complement these simulations by providing students with a virtual replica of the LC MW devices they are studying. This digital twin mirrors the behavior of the physical device, enabling students to explore its performance under different conditions and to identify potential vulnerabilities in the design or modelling processes. For example, students can use the digital twin to simulate the effects of material defects, imperfect fabrication processes, or environmental factors like temperature and humidity, all of which can impact the performance of LC MW devices in real-world applications.

At the outset, a self-contained user manual and recipe are prepared with the "know-how" in place to set up the geometry, discretize the geometry (known as meshing), and solve the meshed elements. Alongside conventional lab demonstrations, the expansive use of digital twinning for digital transformation is a consolidated strategy at a fraction of cost and risk. Students are asked to question the existing knowledge or rule of thumb (e.g., the industry-standardized 50 Ω [44]), and validate it by digital twins with ease.

IV. Vulnerability-Driven Learning and Softwarization

We explore the self-softwarization approach (i.e., shifting the functionalities and mechanisms of the targeted hardware device into software) that is beyond the horizon of mainstream education. One of the most innovative aspects of the course is its focus on vulnerability-driven learning. HFSS of the finite-element method (FEM) [45][46], as well as MATLAB [47–49] and IE3D [50] of general-purpose MoM (method-of-moment) [51] solvers are recommended to dedicated students who learn by seeking vulnerabilities. A pictorial display of these numerical approaches and products is summarized in Fig. 4 and Fig. 5, respectively. Students are encouraged to approach simulation tools not just as a means of verifying known results but as a way to discover and investigate potential flaws in the design or functionality of LC MW devices. This approach aligns with the broader goals of digital transformation in education, which emphasize active, self-motivated learning and the development of critical thinking skills.

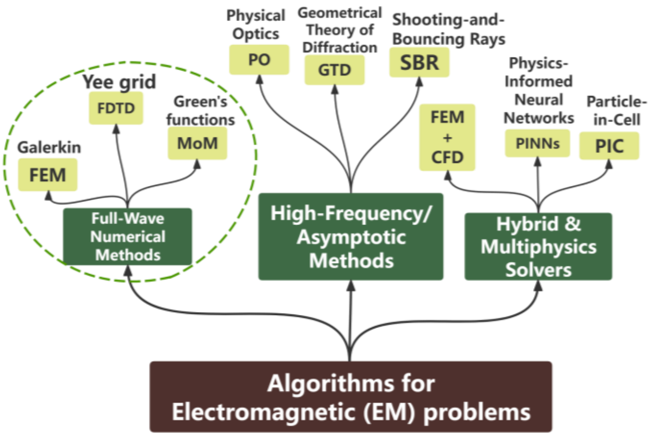

Fig. 4. Algorithms for solving electromagnetic (EM) problems, highlighting the full-wave approaches being adopted by students in the LC MW engineering educational project.

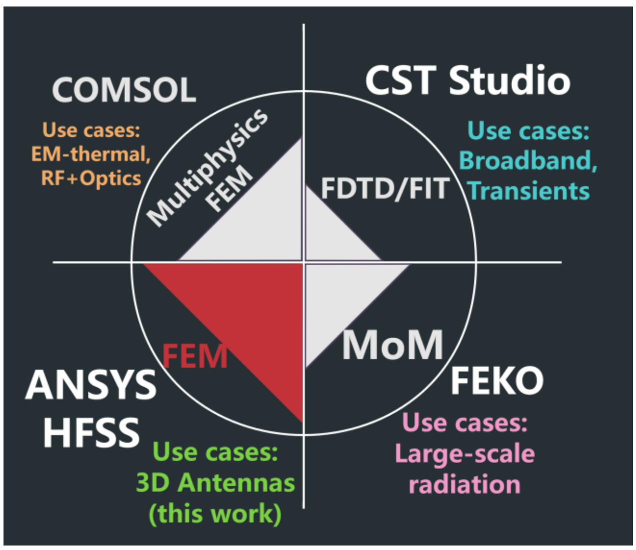

Fig. 5. Numerical solvers accessible to students in the engineering module.

In practice, this means that students are tasked with identifying and documenting vulnerabilities in the EDA tools themselves. For example, they might explore how inaccuracies in meshing algorithms or boundary condition settings can lead to erroneous simulation results. By engaging in this type of hands-on exploration, students gain a deeper understanding of the limitations of the tools they are using and develop the skills needed to address these limitations in future research or engineering practice. The results of these vulnerability studies are collated and analyzed as part of a final project, which challenges students to propose solutions or alternative approaches to the problems they have identified. This not only reinforces their learning but also contributes to the ongoing development of LC MW technology by highlighting areas where further research or refinement is needed.

A. Notch Frequency Drifting Observed by Student

By way of illustration, one of the interesting vulnerabilities that were spotted by a student of this module is showcased here regarding the deviation of the computational prediction of the notch (rejection) of a tunable bandstop filter enabled by liquid crystal (LC) and the quarter-wavelength-based interference mechanism. With technical assistance from our group (supervisor and postgraduate), the undergraduate student managed to spot a new susceptibility of the drift in the resonating frequency from the theoretically designed 60 GHz to 59.6 GHz by simulation, as quantified in Fig. 6.

Via a sanity check with the convergence statistics, the drift observed is precluded from computational errors or design defects. Instead, the impedance-matching baseline [23] tips the balance. In this case study, the minimally achievable dielectric constant of a specific LC employed is used as the impedance-matching baseline. Readers can refer to our tracked record [23][52] for the technical details regarding the tunable LC-dependent impedance matching strategy and its impact.

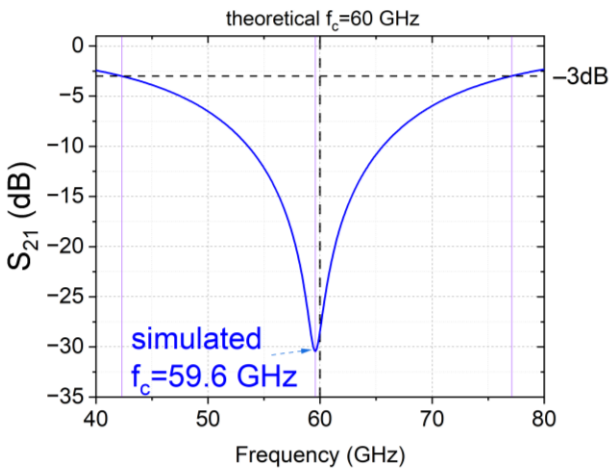

Fig. 6. Resonance frequency deviation (numerical vs. theoretical results) of an LC-filled tunable filter digital twin (theoretically designed with a notch at 60 GHz), as spotted by one of the module students in the computer supported collaborative learning. The geometry of the LC-based filter is designed by the student based on impedance-matching at the minimally achievable dielectric constant of LC.

This drift of 0.4 GHz graphing in Fig. 6, albeit not pronounced, can arguably fail to meet the stringent error budget in ultra-precision filtering applications (if extra calibration efforts are not performed). In this context, the pre-diagnostics work done here is highly informative for guiding the LC-combined notch filter geometry design, in particular, the dielectric constant baseline selection for impedance matching. The deviation database derived herein can be fed into a machine learning-based design framework of LC reconfigurable devices (phase shifters developed in the past [36][40]), and aids in automatically closing the gap between the electrical and physical design [53] of a filter-functioning component.

B. Vulnerability of Line-Length-Parameterization

Another vulnerability observed by a project student involved in the course concerns the line length parameterization (LLP) in one standalone programme during the simulation of liquid crystal coaxial delay line phase shifters of diverse lengths from 1 mm to 30 mm [35]. Compared with independently running these operations (e.g., 30 programs set up for 30 lengths), the sweeping operation in one programme (i.e., one programme covering 30 lengths) negatively results in ambiguity in the zero-phase reference (defined by the calibration line at the wave port, the position of which is impacted by the line length), and hence the deviations in the differential phase shift (DPS) prediction (denoted in red at Fig. 7 as benchmarked with theoretically formulated values).

It is worth noting that a classic yet tuning-efficient architecture, i.e., coaxial transmission line is employed in the simulation-benchmarking test in this vulnerability study for avoidance and resolution of radio frequency interference, i.e., ruling out the crosstalk [23] and the resultant instability issues [16] as observed pronouncedly in the past decade from other state-of-the-art LC-accommodating structures operated in MW and mmW regimes, e.g., inverted microstrip [54], inverted microstrip with a top-launch double-sided design integrated with bias tees [55], coplanar waveguide with a top-floating electrode [45]. Looking back to the current topic of line length parameterization induced vulnerability in DPS prediction errors, as a positive outcome of the student-centered self-directed learning, the student-teacher jointly proposed remediating approach by running individual models separately in multiple programs manages to clear the undesirable DPS errors, as graphed in green in Fig. 7.

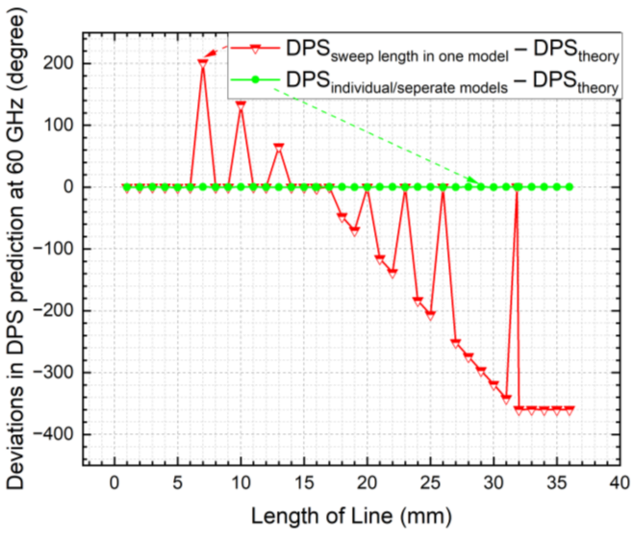

Fig. 7. Differential phase shifting (DPS) errors in computational LLP of an LC-enabled coaxial phase shifter digital twin at 60 GHz by sweeping the line length in one model (denoted in red), as spotted by one of the project students involved in the course. A remediated solution by running separate models of individually defined line lengths (denoted in green) was proposed by teacher and student.

Subsequently, the comprehensive performance index known as figure-of-merit (FoM), defined as the ratio of DPS to insertion loss, is derived in Fig. 8 for the vulnerable single-model approach (denoted in red in Figs. 7 and 8).

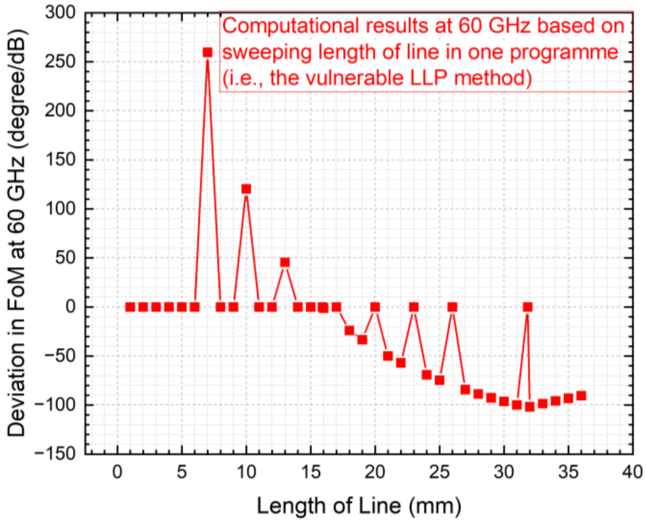

Fig. 8. Differential phase shift-to-insertion loss ratio (i.e., figure-of-merit, abbreviated as FoM) errors in computational LLP of an LC-enabled coaxial phase shifter, as spotted by one of the project students involved in the course.

C. *Vulnerability of Per-unit-length Paradigm Identified*

Interestingly, another line-length relevant vulnerability in computationally characterizing LC-phase shifting devices was derived by a project student in this course during computer-supported collaborative learning, concerning the widely adopted traditional per-unit-length (PUL) scheme to predict the full-length performance via linear scaling.

In this context, figure-of-merit (FoM) comparisons are conducted, among the paradigms of PUL1 (results based on the line length of 1 mm) and PUL2 (results based on the line length of 10 mm), taking the LFP (length-for-pai i.e., results based on the line length of 15.92 mm for 180° shifting) as a benchmarking reference. The superior performance metric by the LFP paradigm is evidenced in Fig. 9 by numerically measuring the results difference in FoM as predicted by the digital twins of PUL1 and PUL2 (conventional paradigms) against the digital twin of the proposed LFP paradigm, across the 60 GHz spectrum from 54 GHz to 66 GHz.

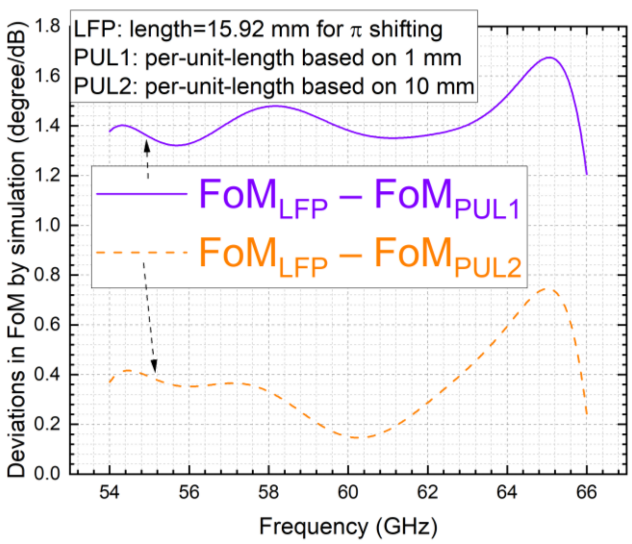

Fig. 9. FoM deviations among the digital twinning paradigms of LFP, PUL1, and PUL2.

On the other hand, it reflects the vulnerability of the traditional PUL framework (PUL1 and PUL2 by way of illustration), which fails to optimally describe the performance potential of an LC-based phase shifter. In another words, through the lens of this comparative action in digital twinning, the conventional PUL baseline for cross benchmarking or performance comparison (as adopted by most documentation in their results discussion parts when comparing their proposed device with states of the arts) is not a scientifically rigorous or fair approach to justify the true performance. A technically sound methodology to remediate the lack of rigor should unify the comparison metric by LFP (i.e., comparing devices with line lengths on the same phase-shifting result of 180° at the same frequency). Note that predicting the results by linearly scaling (normalizing) the line length for 180° also leads to significant deviations, as evidenced by the digital twinning practice in Fig. 9 for FoM.

In summary, the results discussions carried out by existing majority of documents on MW tunable components (not limited to LC MW phase shifters) can provide quick guidance or indication for the respective line length only, i.e., the non-linearity of FoM over line length is where the discrepancy comes into play and overlooked by most research students and engineers. We urge using this digital twin example as developed in the course to alert the community regarding the importance of unifying the phase shifting standard (not the line length standard) during the lifecycle assessment of the LC MW devices.

D. *Boundary Condition Implied Packaging Impact*

Another deliverable spun out from the module was the identification of boundary condition implication [56] on the packaging-induced insertion loss mitigation of an LC-based inverted microstrip phase shifter at 60 GHz, as learned from a project student's simulation practice using the digital twin. Given a fixed inverted microstrip geometry (core line width and LC thickness) and a fixed materials system (involving LC tunable dielectrics, and a non-tunable PCB substrate), perfect electric conductor (PEC)-enclosed packaging, as compared with the semi-open (air-box radiating boundary), exhibits enhanced forward transmission (reduced insertion loss as portrayed in Fig. 10).

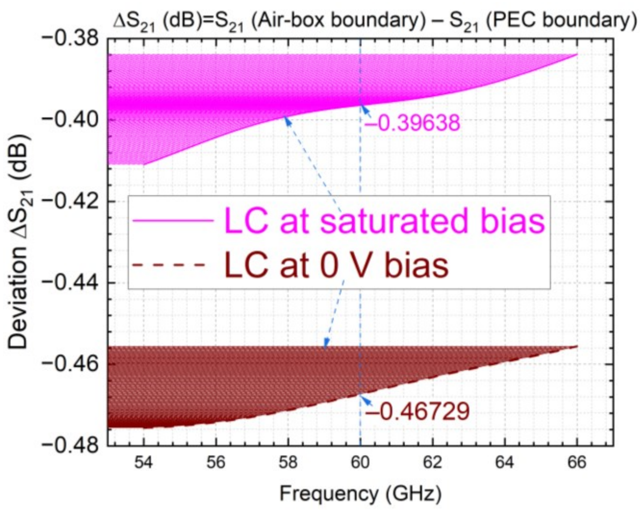

Fig. 10. Insertion loss deviations between perfect electric conductor (PEC) boundary and air-box radiating boundary for an LC microstrip phase shifter digital twin at 60 GHz, spotted by one of the project students involved.

E. Limitations of Current Study and Future Directions

Note that the performance results of LC-enabled variable phase shifters and tunable filters as examined by digital twinning in this work are projected for the 60 GHz spectrum (54 GHz to 66 GHz), with bandwidth and data rate surpassing the current mainstream rollout of sub-6 GHz [57][58] and 28 GHz mmW [59][60] for 5G. Albeit it is conventionally believed that downscaling devices from higher-frequency mmW to lower-frequency MW ones is less challenging and less technically demanding than upscaling of devices and systems from MW to mmW, the vulnerability study evidenced in the digital twins developed in this work demonstrate the discrepancy and deviations of the traditional thinkings. Interesting readers can refer to sections B and C in this chapter for the technical details of the line length parameterization related susceptibilities in differential phase shift prediction and figure-of-merit assessment, respectively.

The digital twins developed in this work are reasonably accurate device-level replicate of the LC component combined with transmission line component. Looking ahead, the next step is to expand the digital twinning framework to encompass a wider range of MW devices and leverage gamification [61][62] for enhanced student engagement and comprehensibility reaching a wider audience. This represents not only a horizontal expansion of other reconfigurable front-end MW devices, but also a leap from devices to networks. This will involve the development of more sophisticated simulation tools and the integration of cross-standard data into the digital twins, enabling students to model and optimize their designs with greater interoperability. Additionally, there is potential to collaborate with industry partners to create digital twins of commercial MW devices, further bridging the gap between academic learning and practical engineering, towards an LC-MW edition of augmented/virtual reality (AR/VR). Big data and machine learning are envisaged to play a big part in the new LC material synthesis, and new devices development.

Beyond the digital twins developed at the device level in this work, a digital replicate of LC phase shifting based feeding network as a sub-system for a phased array antenna system shall be deployed next, targeting beam steering and tracking services in urban, suburban and remote areas. Aligning with the 6G vision, the LC-based phased array system shall be integrated with satellite internet [24][63][64] for non-terrestrial (including inter-satellite communications [65]) and more broadly speaking, space-air-ground-sea networks [66] for ubiquitous coverage.

Accordingly, LC-embedded digital twins should be expanded to integrate satellites (space), drones (air), and underwater (sea) communication (and sensing facilities for seamless global connectivity. Densifying the infrastructure will arguably lead to power consumption and resiliency issues, for which the envisaged zero-energy devices capable of wirelessly harvesting ambient MW [67–70] or optical [71–74] power, alongside with other efficient harvesting methods [75–82] can be included in the next-phase educational transformation of LC microwave engineering teaching (and student-centered learning) for closing the gap of the net-zero vision [83–89], particularly from the lens of integrated circuits (IC) manufacturing [90], wherein the impacts' quantification of micro-vias embedded devices with LCs have been kicked off in [91], concerning the degradation in not only the forward transmission coefficient (i.e., insertion loss [92]), but also in the differential phase shift [91] across 1 GHz to 67 GHz (the use of V for high-capacity backhaul solution in densely populated urban regions).

Looking ahead, the terahertz (THz) gap—albeit gradually being bridged in broadband spectroscopy and imaging applications [93]—remains a compelling research subject due to persistent physical constraints and an incomplete understanding of wave-modulation mechanisms.

This is particularly true in the context of LC-based reconfigurable systems [94–97], where tunable dielectric-induced phase shifting or time delaying (Fig. 11) holds significant potential for 6G beam-steering, beam-scanning and beam-tracking, targeting integrated communications and sensing with enhanced physical-layer security [98][99].

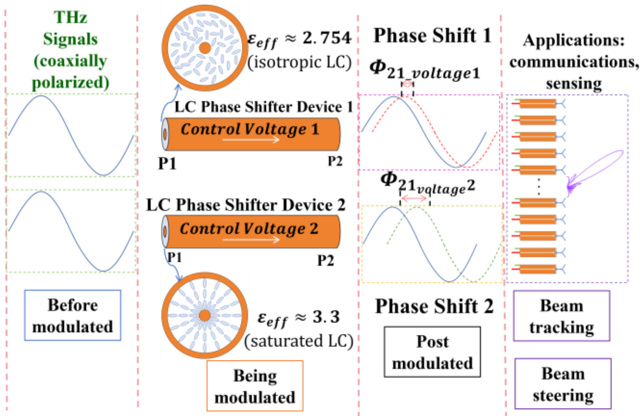

Fig. 11. Depiction of THz waves' reconfigurability in voltage-controllable phase shifts (or time delays) produced by a classic coaxial delay line filled with LC.

Additionally, near-field optics [100][101] are becoming increasingly relevant, especially in indoor environments (e.g., conference rooms), where their influence can dominate wave propagation. Unlike conventional far-field spherical wave approximations—commonly assumed in lower-frequency wireless communications—near-field wavefronts exhibit distinct characteristics, necessitating a reevaluation of existing models for high-frequency systems. For prospective researchers working on sub-mmW (THz) component fabrication, additive manufacturing techniques (e.g., 3D printing [102]) offer a promising alternative to conventional PCB etching, which remains effective primarily for RF and microwave frequencies.

V. Conclusion

Edging closer to the next-generation transformative communications (to be rolled out in full swing from 2030), the integration of digital twinning and digital transformation strategies into the teaching and learning of liquid crystal (LC) millimeter-wave (mmW) technology for 6G represents a significant step forward in microwave engineering education. By leveraging EDA simulation tools and vulnerability-driven learning in digital twins, the States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G course provides students with the knowledge and skills needed to navigate the challenges of the 6G era.

Aiming at not just addressing the key engineering challenges in LC microwave (MW) and mmW devices, but also at identifying the critical knowledge gaps, this work provides an interesting engineering exploration of educational approaches for 6G networks, based on decades of heritage in LC-based tunable device developments. As evidenced in the case study conducted and reported in this paper, the introduction of digital twinning-targeted digital transformation into the smart classroom for the undergraduate module entitled “States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G” has yielded several positive outcomes and tangible real-world implications.

First, the explorative course has provided students with a more engaging and interactive learning experience, allowing them to explore the complexities of LC MW technology in a risk-free digitally twinning environment. Second, it has fostered a culture of innovation and critical thinking by encouraging students to question established norms (e.g., 50 Ω) and investigate the limitations of existing tools (e.g., the vulnerable line-length-parameterization spotted in a full-wave finite-element numerical method solver named HFSS) and techniques (e.g., the per-unit-length paradigm), as validated by digital twinning based testing. Moreover, the vulnerability-driven approach has proven to be an effective means of preparing students for real-world challenges in the 6G era. By identifying and addressing potential flaws (four kinds of major susceptibilities as reported above) in their designs, students managed to develop the problem-solving skills needed to succeed in an industry (ecosystem) that is constantly evolving.

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