Will 'Liquid-Crystal-Based Floating-Electrode-Free Coplanar Waveguide Phase Shifter With an Additional Liquid-Crystal Layer for 28-GHz Applications' Work?

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Abstract—**The growing interest in the modulation of phase (and amplitude) of microwave and millimeter-wave signals has been spurred by the emerging 5G/6G phased-array beam-steering applications for which liquid crystal is one of the enabling technologies. A problematic journal paper on liquid crystals-based coplanar waveguide phase shifters is scrutinized in this letter to urge readers and a wider academic community's attention. Specifically, concerns have come up about the usefulness, effectiveness, and accuracy of the simulation-only work that Jun-Seok Ma et al published recently at J. Phys. D: Appl. Phys. 55 095106, entitled 'liquid-crystal-based floating-electrode-free coplanar waveguide phase shifter with an additional liquid-crystal layer for 28 GHz applications'. With no devices fabricated and no experimental measurements, the simulation results and conclusions are subject to fundamental yet important errors (significant overestimations) that can mislead readers as well as researchers truly working in the field of liquid crystals-based tunable microwave and millimetre-wave devices. The lack of experimental data means that the validity and reliability of the simulation results cannot be fully assessed. A reflection on other drawbacks of the article is also elaborated in this letter.**

Index Terms—**Antenna array feed, coplanar waveguide, liquid crystals, microwave, phase shifter, tunable dielectrics**

I. Introduction

IN recent decades, advancements in nematic liquid crystals (LC) enabled reconfigurable components [1][2] and subsystems level [3] developments are steadily evolving microwave (MW) and millimetre-wave (MMW) technology to provide indispensable functions for phased-array non-mechanical beam steering with continuous-tuning (analog resolution) [4], low-insertion-loss [5], as well as lighter, smaller, and less power-hungry [6] properties targeting end-users and technologists in various industrial settings, such as satellite communications [7], astrophysics instrumentation [8], biomedical systems [9], and critical infrastructure monitoring. Each new generation of designs (evidenced in new device structures [10], or materials innovation [11]) fuels the demands of end-users a little more and results in follow-up incremental contributions to Information and communication technologies (ICTs) services, though the true commercialization of LC MMW systems has yet to arrive, due to a host of challenges specified in [12], including but not limited to the cost, response time, and reliability. There are a few newly published excellent works in 2021-2022 that are striving to bring new knowledge to this field. By ways of illustration, paper [13] presents an electronically variable dielectric image line leaky wave antenna based on LC at W band from 75 GHz to 102 GHz. The work reported in [14] analyses a figure-of-merit mismatch phenomenon found between the LC material itself and the LC-based phase-shifting devices examined at 60 GHz. Additionally, for the first time, paper [15] introduces a LC-based fully-electronically tunable waveguide filter that is reconfigurable in bandwidth and center frequency.

This letter aims to draw the attention of the academic community to a problematic article by Jun-Seok Ma et al., titled 'liquid-crystal-based floating-electrode-free coplanar waveguide phase shifter with an additional liquid-crystal layer for 28 GHz applications,' published in J. Phys. D: Appl. Phys. 55 095106 [16]. The paper [16] is scrutinized due to concerns about the usefulness, effectiveness, and accuracy of the simulation-only work, which lacks experimental validation, and contains fundamental errors that may mislead readers and researchers in the field of LC-based tunable MW and MMW devices. This letter reflects on the limitations of the paper and highlights the need for more comprehensive experimental data to validate simulation results in the field.

Section II investigates the main flaws spotted, the coverage of which includes the definition mismatching regarding "floating-electrode-free", the absence of fringing-field calculations, a lack of understanding of the limitations of the alignment layer's anchoring capability, duplicating equations without adding to the existing body of knowledge, missing devices' fabrication, and no measurements conducted, etc. Technical suggestions are provided accordingly, targeting both the authors (who are suggested to remediate the faults in their future study) and readers (who should be aware of the faulty statements claimed in the article under comment [16]. While the lack of experimental data limits the validity of their results [16], their simulation-only study could still provide a starting point for future work that may involve both analytical innovation (applying existing equations in new ways with unique interpretations) and experimental validations.

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II. Analysis of Flaws Spotted

The flaws spotted for [16] are summarized in Fig. 1 and analyzed in the following sections, respectively. These issues may have led to false-positive or false-negative results and compromised the validity of the conclusions drawn by [16].

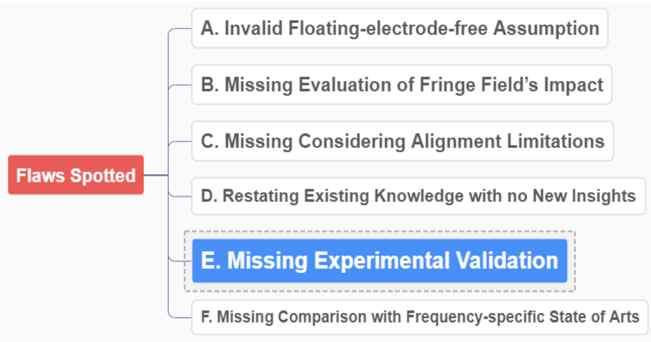

Fig. 1. Flaws identified for the article under criticism.

A. *Invalid Floating-electrode-free Assumption*

First and foremost, the statement of the "floating electrode (FE)-free" is not rigorously valid. The conductors' arrangement in the proposed device configuration of the paper [16] under comment is arguably a conventional coplanar waveguide but without unifying (wire-bonding) the two coplanar groundings on the left and right sides, as sketched in Fig. 2, which identifies the floating electrodes on the two coplanar grounds. A top non-metal substrate (and spacers) is employed to encapsulate the additional LC layer. Mode analysis for the structure, which was missing in [16], is performed in this letter and reported in Fig. 3 below.

From device physics and experimental practice over decades at MW and MMW frequencies, the ununified coplanar grounds can create unequal electrical potentials (as the removed top floating electrode did), leading to the susceptibility to higher-order slot-line modes (illustrated in Fig. 3) and newly introduced floating electrodes on the two coplanar grounding sides of diverse potentials (V), i.e., V (left-floated) and V (right-floated), respectively.

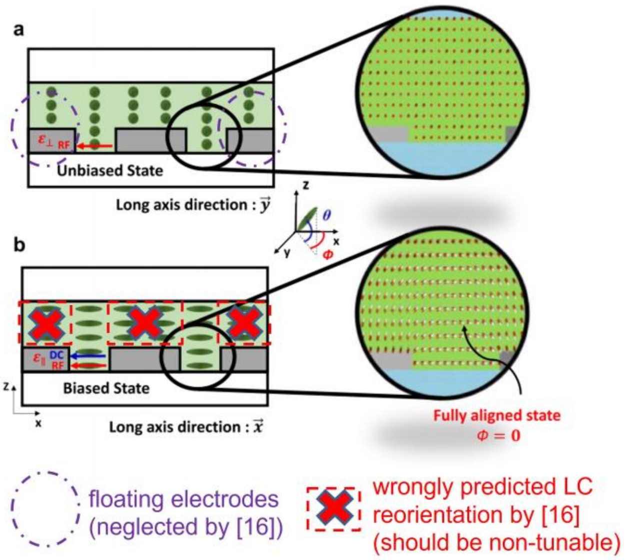

Fig. 2. Schematic redrawn from [16] for re-investigation of flaws identified: (a) Identification of two coplanar floating electrodes (overlooked by [16]); (b) Identification of wrongly predicted LC reorientation regions by [16].

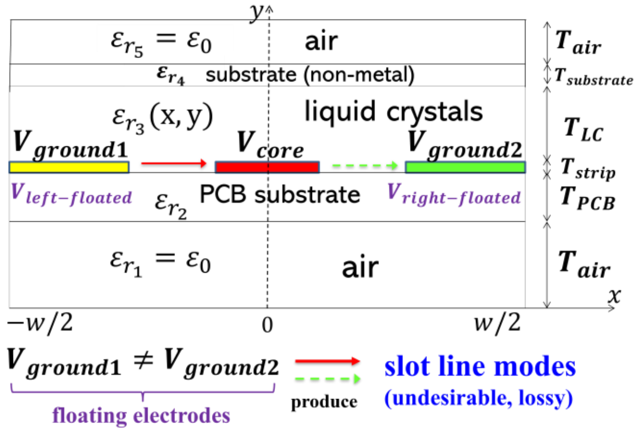

Fig. 3. Undesirable higher-order slot-line modes excitation for the problematic structure at MW and MMW frequencies. Yellow, red, and green boxes (from left to right) represent the cross-section of grounding metal on the left, core line metal, and grounding metal on the right, respectively.

The floating electrodes will lead to a variety of instability issues (very lossy) at MW and MMW frequencies (e.g., surface-wave radiation, coupling of modes), for which single-mode simulation will not tell anything but the authors fail to realise this and have yet to experimentally demonstrate that if it is an issue or not for their proposed configuration at this frequency. The more appropriately defined topology here should therefore be claimed as "top-electrode-free", instead of the misleading "floating-electrode-free". The main drawback of a floating electrode is that it is susceptible to noise and interference from the surrounding environment. Since it is not connected to any external reference, any electrical noise or interference that enters the system can cause the voltage on the electrode to fluctuate, which can result in inaccurate measurements. To address this issue, some methods can be used, such as shielding the electrodes or using differential amplifiers to amplify the voltage difference between two floating electrodes, which can help to cancel out the common-mode noise. However, these methods can increase the complexity and cost of the system.

B. *Missing Evaluation of Fringing-field's Impact*

Even from the perspective of a simulation-only paper (under an erroneous assumption that experiment is not compulsory), the tuning range and figure-of-merit benefits are highly overestimated in the paper [16] under comment, as the authors fail to account for the fringing field in the additional liquid crystal (LC) layer, in particular the region above the core line electrode. As sketched in Fig. 4 here for analysis, the only effective tuning enabler is mainly the LC volume within the two coplanar channels (bounded by the long and short dashes denoted in blue).

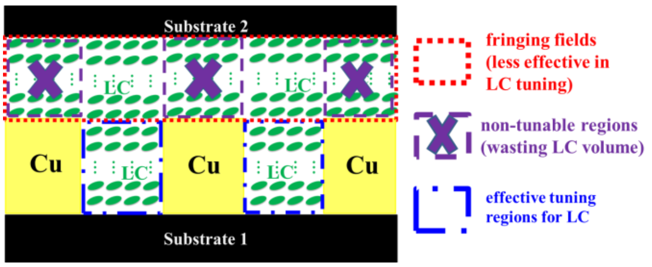

Fig. 4. Re-investigation of the region-wise LC tuning principle (not reflected in the problematic device structure of the article under criticism).

However (as overlooked by the authors [16]), the additional LC layer (in the volume bounded by the small dashes denoted in red at Fig. 4) should be far less effective in contributing to the overall tuning functionality (i.e., differential phase shift). In the absence of a top electrode (as shown above in Fig. 4), the volumes bounded by longer dashes and denoted in purple crosses (right on top of the core line as well as the two grounding electrodes) are the least effective tuning regions (arguably non-tunable) for LC. For the additional LC layer, the only effectively tunable region is the fringing field that is strongest at the edges of the core line conducting strip, where the electric field lines curve outward and extend into the LC around the core line. The strength of this fringing field can be controlled by adjusting the width of the conducting strip and the distance between the conducting strip and the ground planes. This underpinning region-wise tuning principle is however not reflected in the paper [16] under comment.

For the paper under comment [16], there is no evidence showing their consideration of this fringing field and non-tunable regions (essentially a waste of the LC volumetric media and adding unnecessary material costs). Their simulation results and discussion in section 3 of the paper [16] (and hence the conclusions they have drawn) are thereby invalid. To be more specific, in Fig. 2 (b) of the paper under comment [16] regarding the fully biased state, the LC director's alignment can by no means be as ideal as the case that is shown. Without an electrode on the top, the field at the additional LC layer is arguably a fringing field that makes the driving of the LC director at the additional layer to be significantly less effective than that is analyzed/predicted by [16]. There are many excellent references [17][18] on capturing the fringe-field switching to improve the LC-based device's performance (mainly to improve response speed and lower the driving voltage, i.e., reduce the power consumption), from which the authors [16] could reflect on.

Nevertheless, to make use of the "additional LC layer" for a decent tuning range, a top electrode should be in place (referring to the established works on LC-based inverted microstrip [19][20] and LC-based enclosed coplanar waveguide [21] that are experimentally verified). In summary, the proposed additional LC layer and targeted high-tuning-range top-electrode-free structure are not compatible in one design, due to structure-induced fringing field that compromises the tuning range and efficiency significantly.

C. *Missing Consideration of Alignment Limitations*

Furthermore, the thickness increase of the additional liquid crystal layer claimed in the paper under comment [16] should practically be limited by the alignment layer's anchoring ability (mechanically anchoring), for which the authors fail to take this into account completely in the simulation, the conclusion based on which (e.g., by increasing the LC thickness to 300 μm as shown in Fig. 5) is of no practical use at all for real-world device making and commissioning.

Thereby, the proposed structure and analysis in the paper [16] under comment can be considered misleading due to the lack of consideration of the limitations of LC pre-alignment. The failure to consider these limitations can result in unexpected behavior and decreased reliability of the device. For example, the device may not be switchable, meaning that it cannot reorient, or respond at an extremely slow rate when the voltage bias is removed. In Fig. 5, an increase in the thickness of the LC layer from 150 μm to 300 μm should have resulted in a decrease in the Figure-of-Merit (FoM), which is defined as the ratio of maximum phase shift to maximum insertion loss. The authors' observations of a saturating phenomenon may not necessarily be indicative of the expected behavior of the FoM under these conditions. Alternatively, the device may require a surge of voltage bias to reach the switching threshold, which would be a compromise to the low power consumption advantage exhibited by LC. Additionally, the linearity of the voltage-phase shift response may also be distorted. Such issues can lead to unpredictable performance and make it difficult to optimize the device for specific applications, which is crucial for its practical implementation. Therefore, it is essential for researchers to take into account the limitations of LC pre-alignment and thoroughly analyze their proposed device structures to avoid any misleading claims and to ensure that their designs exhibit the desired performance characteristics.

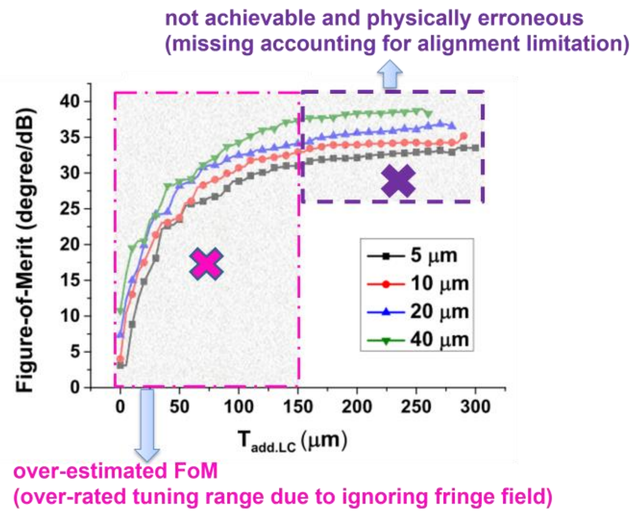

Fig. 5. Evaluating the invalid simulation results from the problematic device structure of the article under criticism.

Consideration must also be given to the power efficiency for a large array targeting 5G use cases, the challenging criteria of which requires robust and well-defined LC alignment and pre-alignment approaches in the experimental design (arts in manufacturing). However, the unreasonably simulated thicknesses in [16] will lead to difficulties in manufacturing and integration, and ultimately increased costs and longer development times. These will jointly compromise the overall performance (suboptimal) and even the viability of the device for practical use.

D. *Restatement of Existing Knowledge without Offering New Insights*

It is also well worth noting from the paper [16] under comment that the equations (2)(4)(7)(8)(9) displayed, as well as the tuning range and wave-occupied-volume ratio concepts mentioned, were all duplicated (though partially referenced) from our previously published works [21][22][23]. However, there is no evidence showing any new theoretical or methodological development in this paper [16] under comment, given that no experimental work is presented to validate the "new" structure. Furthermore, the simulation effort mentioned in section 3.1 of the paper [16], entitled "analysis of FE-free CPW phase shifter without an additional LC layer" is duplicating our previously published work [22] at the 46th European Microwave Conference.

Duplicating existing equations but providing proper citations to sources and giving credit where it is due is not necessarily a negative thing. However, if the paper lacks new theoretical contributions, it can be considered as limited in its scientific value. While proper citation is necessary, it is not enough to make up for a lack of original content. A strong paper should not only properly acknowledge its sources but also provide novel insights and contribute to the advancement of knowledge in this field. As such, the paper under criticism [16] should have been seen as insufficient scientific rigor and novelty for publication in a reputable academic journal like Journal of Physics D: Applied Physics.

E. Absence of Experimental Validation

It is inappropriate to purport in the abstract that the proposed phase shifter "is demonstrated". All statements and conclusions by the paper [16] under comment are derived from parametric simulations only and have yet to be validated. Contrarily, there is no evidence demonstrating that any experimental work is conducted. No devices are fabricated, and no measurement results are reported in [16] under comment. The interpretation of the simulation results is flawed as it goes beyond the scope of the LC device manufacturing and extrapolates the findings without adequate experimental evidence.

It is lacking experimental evidence to claim in the conclusion section of [16] that they have "confirmed a peculiar tendency". Confirming this tendency requires fabricating and measuring a couple of devices with different electrode widths and accordingly different thicknesses of the additional LC layer. In paragraph 4 of the introduction section [16], the authors did admit that their paper only proposes a simulated model, but they purported to have "demonstrated" the phase shifter structure here as well as in several other parts of the paper, including the abstract and conclusion, which is severely inappropriate and can mislead academics working in this field.

F. Absence of Performance Comparison with Frequency-specific State of the Arts

Last but not least, the paper [16] under comment targets the application scope in the regime of 28 GHz as the frequency under analysis. Note that the established LC-based device structures widely acknowledged at Ka-band frequencies around 30 GHz are inverted microstrips and dielectrically filled metallic waveguides [24], while state-of-the-art coplanar-related structures are experimentally reported for 60 GHz [21] and beyond [23]. For the selected 28 GHz, the authors [16] are suggested to add experimental results of their proposed device structure compared to existing documentation to confirm the validity and significance, i.e., avoiding being of no interests for applications in the real world.

It is widely acknowledged that to accurately evaluate the novelty and potential impact of any proposed device structure solution, it is crucial to have a comprehensive understanding of the current state of the art in the field. Without such a comparison, it becomes difficult to determine the true level of innovation and improvement that the proposed solution brings to the table. Furthermore, a lack of comparison can also prevent the paper from effectively showcasing the significance of the work and identifying areas for future research and improvement. For instance, it would be valuable to explore how the proposed solution can be fully integrated into a reconfigurable MW/MMW system to enable adaptive and flexible performance. Thus, it is important for researchers to provide a thorough analysis of the existing literature and highlight the advantages of their approach compared to prior work in the field to advance the state-of-the-art in the area. Note that the advantages justification must be conducted by experimental measurements.

Once experimentally verified and compared with the state of the art, it would then be interesting to understand the target application. As most researchers understand, LC is relatively slow to reconfigure for any near real-time tuning applications. To determine the most suitable technology for a specific application, researchers need to understand the requirements and constraints of the target system, including speed, power consumption, size, and cost. By considering these factors and comparing different technologies (not restricted to LC but including Micro-Electro-Mechanical Systems [25] and others), researchers can determine the best approach for achieving their desired results.

III. Concluding Remarks and Outlook

Designing a novel LC phase shifter requires a combination of new theoretical modeling, experimental testing, and experimental optimization to achieve the desired performance characteristics. This letter scrutinizes and flags a simulation-only paper [16] with unvalidated statements and erroneous observations that merit reinvestigation by experiments. Basic errors and faulty judgments in LC-based device design and simulation are pointed out. It is kindly recommended that the authors could address the above concerns by re-modelling, prototyping, and measuring a number of designs of different geometry sizes they proposed to validate the conclusions they have published. Without experimental evidence, the article will be continuously subject to criticism in many aspects by readers, from conceptualization to simulation results and conclusions, which have yet to be validated scientifically. The paper under comment does provide a starting point for future work, but the findings should be considered with caution until they are supported by experimental evidence. It would be ideal to see the results of this study validated through experiments in the future. By way of illustration, a decent example of the recommended work packages sequence can be referred to [26], starting from design, simulation to fabrication, experiments, measurements, and benchmarking/comparison.

Looking ahead to a broader perspective, not only are

MW/MMW reconfigurable systems expanding in their traditional application fields (e.g., telecommunications and defense/security sectors), but most recently, we have seen expanding applications in consumer devices, which demand higher degrees of integration and cheaper hardware. At the frontier of such research and development, experimentally executing a vast array of designs is mandatory to not only truly answer the fundamental questions of how LC materials and MW/MMW transmission lines/waveguides can optimally combine, but also to convince the potential customers who are unfamiliar with the LC based MW/MMW technology (and hence are hesitant to adopt the untested technology like the one [16] under criticism) regarding the strengths and weaknesses against industry opportunities and requirements.

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Prof. Li was a recipient of the IET Award, the AP Jarvis Prize, and two Best Paper Awards at the IEEE and IOP conferences, respectively. He was a Cambridge Trust Scholar, Speaker at the 50th & 46th European Microwave Conferences, Emerging Technologist with Barclays UK, Editorial Board member of 3 Science Citation Index journals, TPC and Session Chair of 5 IEEE conferences, including IEEE ISAP (27th International Symposium on Antennas and Propagation), and IEEE 15th International Conference on Microwave and Millimeter Wave Technology (ICMMT 2023). He was the Top 1% Reviewer on Publons (Web of Science), Reviewing Expert for the China Academic Degrees and Graduate Education Development Center, Newton Prize (£1m fund) reviewer for the UK National Commission for UNESCO, and grants reviewer for Health and Social Care Delivery Research (HSDR) fund from National Institute for Health Research (NIHR), UK.