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Meta-Material Engineering for Tunable Electromagnetic Wave Control in (6G) and Future Communication Networks

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Abstract

Tetrahertz and sub-terahertz frequency bands must be used to handle 10Gbits/s of data for sixth-generation (6G) wireless networks to work. For example, in dynamic mobile settings, these high-frequency bands are easily stopped because the air absorbs them very well. Thus, inactive mirrors and static antennas are unable to assist the messages in getting where they need to go. To get around this basic issue, this study provides a formal engineering framework for electromagnetic metamaterials that can be altered and can be utilized as a physical control layer that can be altered. Active unit-cell designs that can make dynamic surface resistance are part of our job. To support this, we use full-wave electromagnetic simulators and similar circuit models. In this study, each way of tuning is carefully looked at. Finding the best balance between phase tuning range, insertion loss, and switching delay is done by comparing electronic varactor biasing and material phase-change methods. This article demonstrates that these bendable surfaces bridge the gap between the physics of the device and the performance of the whole system. This allows us to exactly shape the wavefront for tasks such as real-time beam

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steering and hologram focusing. The results look into how electromagnetic control affects the network's dependability. In difficult non-line-of-sight situations, they show that the signal-to-interference-plus-noise ratio and coverage chance get a lot better. Metamaterials that are intended to be active are not just extra bits, as these results show; they are important structures to make sure that 6G transmission is stable, scalable, and energy-efficient.

Keywords: Metamaterials; 6G communications; tunable electromagnetic surfaces; THz propagation; intelligent reflecting surfaces.

هندسة المواد الفائقة للتحكم القابل لضبط الموجات الكهرومغناطيسية في شبكات الجيل السادس (6G) والاتصالات المستقبلية

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الملخص

يجب استخدام نطاقات ترددات التيرا وما دون التيرا لمعالجة بيانات بسرعة 10 جيجابت/ثانية لكي تعمل شبكات الجيل السادس (6G) اللاسلكية. على سبيل المثال، في بيئات الاتصالات المتنقلة الديناميكية، تُحجب هذه النطاقات عالية التردد بسهولة لأن الهواء يمتصها بكفاءة عالية. وبالتالي، تعجز المرايا غير النشطة والهوائيات الثابتة عن مساعدة الرسائل في الوصول إلى وجهتها. وللتغلب على هذه المشكلة الأساسية، تقدم هذه الدراسة إطارًا هندسيًا رسميًا للمواد الكهرومغناطيسية الفائقة القابلة للتعديل، والتي يمكن استخدامها كطبقة تحكم فيزيائية قابلة للتعديل. وتُعدّ تصميمات الخلايا الوحدوية النشطة التي تُتيح مقاومة سطحية ديناميكية جزءًا من عملنا. ولدعم ذلك، نستخدم محاكيات كهرومغناطيسية كاملة الموجة ونماذج دوائر مماثلة. في هذه الدراسة،

نُمعن النظر في كل طريقة من طرق الضبط. ويتم إيجاد التوازن الأمثل بين نطاق ضبط الطور، وفقد الإدخال، وتأخير التبديل من خلال مقارنة طرق التحيز الإلكتروني للمكثف المتغير السعة وطرق تغيير طور المادة. تُبيّن هذه المقالة كيف تُسهم هذه الأسطح المرنة في الربط بين خصائص الجهاز الفيزيائية وأداء النظام ككل. وهذا يُتيح لنا تشكيل جبهة الموجة بدقة متناهية لمهام مثل توجيه الحزمة في الوقت الفعلي وتركيز الهولوغرام. وتتناول النتائج تأثير التحكم الكهرومغناطيسي على موثوقية الشبكة. ففي حالات انقطاع الاتصال المباشر، تُظهر النتائج تحسنًا ملحوظًا في نسبة الإشارة إلى التداخل والضوضاء، فضلًا عن تحسين فرص التغطية. وكما تُبين هذه النتائج، فإن المواد الفائقة المُصممة لتكون فعّالة ليست مجرد وحدات إضافية، بل هي هياكل أساسية لضمان استقرار نقل بيانات الجيل السادس وقابليته للتوسع وكفاءته في استهلاك الطاقة.

الكلمات المفتاحية: المواد الفائقة؛ اتصالات الجيل السادس(6G) ؛ الأسطح الكهرومغناطيسية القابلة للضبط؛ انتشار موجات تيراهيرتز ؛ الأسطح العاكسة الذكية.

1. Introduction

Making sure people can connect is no longer enough as we move toward sixth-generation (6G) wireless networks. Now we need to build the radio world itself. Millimeter waves were used to make 5G networks faster. According to Tataria et al. (2021), 6G will make even bigger jumps into the terahertz (THz) and sub-terahertz spectral bands so that it can handle data rates above terabits per second and delays of less than a microsecond. On the other hand, these high-frequency bands cause major electromagnetic (EM) problems that can't be fixed by normal receiver designs. Free space is not a good place to talk because the transfer frequency goes up very quickly. You can see clear absorption peaks when you work with molecules in the air, like oxygen and water vapor. Path loss grows in a quadratic way. More importantly, electromagnetic waves are very sensitive to solid blocks at THz levels because the bands are so small. Deep shadowing effects happen in places where there is almost no non-line-of-sight (NLoS) link. Not having enough bandwidth isn't the only problem with developing 6G. We also can't control how electromagnetic waves move through the real world, which is messy, always changing, and not always welcoming.

To make wireless systems in the past, the broadcast channel was seen as random and out of their control. It was like a "black box" with uncertain fade models (Rayleigh, Rician) that they had to deal with instead of changing. In order to make up for route loss, traditional methods like beamforming and big Multiple-Input Multiple-Output (MIMO) rely on radio bands with a high gain. All of these active technologies can do, though, is direct energy at the source.

Because of this need, electromagnetic metamaterials and meta surfaces have been created. These are man-made materials with subwavelength unit cells that have electromagnetic qualities that there are weird ways you can change attitudes and reflect with this. Because of these traits, the idea of Reconfigurable Intelligent Surfaces (RIS) in wireless connectivity came about. By rerouting signal energy in a smart way, these surfaces can keep link budgets in non-locality of service (NLoS) cases (Basar et al., 2019; Liu et al., 2021). When it comes to the system level, RIS shows a lot of promise, but there is still a big gap between how these surfaces are talked about in communication books and how they are used in the real world, especially at THz frequencies.

At the time, metasurface research is mostly split into two areas: physics at the device level and signal processing at the network level. A lot of study is being done on things that make it easy to tune individual unit cells. In these papers, phase-change materials like Vanadium Dioxide (VO_2) or micro-electromechanical systems (MEMS) are used (Sun et al., 2020; Zhuang et al., 202^{3}). But these works don't always look at the problems that happen when they're used on a big scale, even though they have some really cool moving parts. That is, they don't always think about things like control delays, how much power the biasing network needs, or how phase quantization and spectral efficiency compare to each other. "Phase-shifting" surfaces are used a lot in communication theory, on the other hand. The reaction is simple, and the timing control is always the same. Since frequencies spread, ohmic losses happen, and cells talk to each other, THz deployments aren't as useful in real life (Jia et al., 2020). Things like these are not looked at in these studies. The science behind the materials used in networks doesn't seem to have much to do with how well they work because this is too easy. This can lead to predictions of performance that might not be accurate in real life.

The metamaterial needs to be looked at as a complicated electromagnetic control system, not just a simple sheet, so that these problems can be solved. By giving a full mechanical breakdown of tunable metamaterial engineering made just for 6G uses, this paper fills in the gaps between material physics and network design. We think that EM control needs to be improved in a number of ways in order to work well. The first step is to make unit cells that can be changed and have the lowest loss tangents possible. After that, we need to find the large-scale impedances at the surface. Lastly, we need to look at metrics that measure the whole system, such as SINR and covering chance. This article goes into more depth about the physical changes that happen when you tune in different ways. The fast but lossy designs based on graphene are compared to the high-linearity but slower reaction of liquid crystal and MEMS methods (Squires et al., 2022; Wang et al., 2024) to show this.

To make and test a full design framework for customizable metasurfaces that takes sub-THz transmission limits into account is the most important thing that this work does. The math model we show has a direct link between the network's channel state information (CSI) and the unit cell's surface susceptibility that changes with bias. We show that the shape of the meta-atom resonance and the addition of varactor tuning networks are some of the technical choices that limit how accurate beam steering can be and how wide the bandwidth can be. There are more options than just the "black box" idea. We look into the part of metasurfaces that code space-time even more. It breaks equality and lets us change frequencies, which gives us more ways to stop interference (Shaltout et al., 2019; Karl et al., 2020).

2. Literature Review

As an example of how materials science and wireless communication theory are coming together, electromagnetic control has gone from having big, static parts to having small, moving systems that are built into the surface. The first studies were mostly about the basic science of materials with a negative index. But 6G networks need metasurfaces that can be changed, written, and coded in order to work. This is especially true for sub-THz frequencies where beamforming and blocking need to happen very quickly. This part takes a close look at the newest developments in metamaterial engineering. It shows how theoretical ideas are different from hardware that can be built and what the pros and cons of various ways to tune the materials are.

2.1 Metamaterial Fundamentals for Electromagnetic Control

Metasurfaces are built on switching from the volumetric Effective Medium Theory (EMT) that rules metamaterials in the bulk to surface impedance boundary conditions. Bulk metamaterials use Three dimensional groups of resonant features to make effective permittivity (ρ_{eff}) and permeability (μ_{eff}). Metasurfaces make sharp phase changes (Φ) at a two-dimensional contact. What controls

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this process is Generalized Snell's Law (Holloway et al., 2012), which says that the direction of the wave that is sent or mirrored depends on the change in the phase gap in space (d⁄dx) (figure 1).

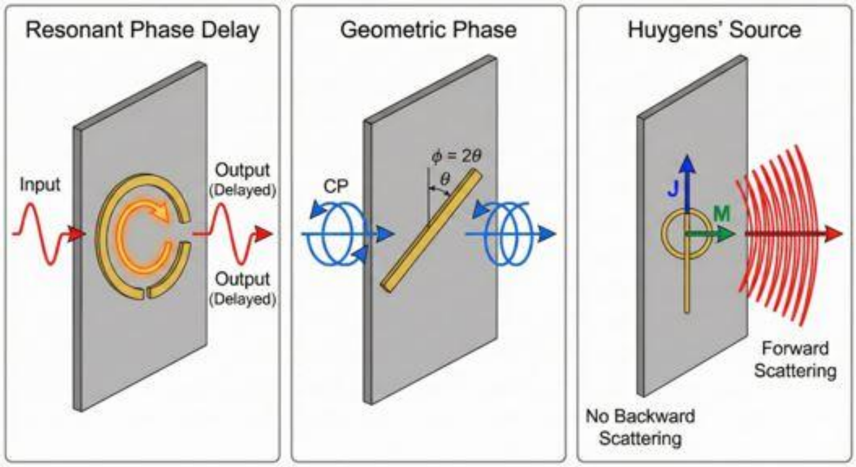

Fig. 1. Three main for Phase control in electromagnetic system.

The Frist method, resonant Phase delay , uses resonant structures to introduce a Phase shift in the transmitted signal, although it is limited by a narrow bandwidth. The second method, geometric Phase, controls the Phase by rotating elements, where the phase shift depends on their orientation. The third method, Huygens source, is based on the balance between electric and magnetic responses, allowing efficient forward transmission while reducing back ward scattering. These methods represent different techniques for manipulating wave propagation.

2.2 Tunable and Reconfigurable Metamaterials

Adding elements that can be changed into the structure of meta-atoms is key to making adaptable electromagnetic control work. There are a number of different competing ways to achieve this tunability, and each has its own effects on switching speed, power consumption, and working frequency. It's not just the device level

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that decides which method to use; it's also the system level that limits how the metasurface can be used in certain 6G situations.

- **Electronic Tuning (Varactors and PIN Diodes)**

Varactor-loaded and PIN diode-integrated metasurfaces are the most advanced technologies for microwave and low-millimeter wave bands. When you reverse-bias a varactor diode, you can change the capacitance of the corresponding LC circuit in the unit cell. (Zhao et al., 2019) say that this changes the mirror phase and the resonance frequency. Because this physical setting stays the same, the time can be controlled very exactly. Industrial mixed elements have too much parasitic resistance and inductance when frequencies get close to sub-THz, though. This leads to big insertion losses. Tang et al. (2019) also say that it is hard to scale up because the biasing network is very complicated and needs different control lines for thousands of unit cells.

- **Phase-Change Materials (VO_2 and GST)**

VO_2 and GST are phase-change materials that researchers have looked into as a way to get around the problems that come with grouped elements at THz frequencies. When VO_2 is introduced to heat, electricity, or light, it can change from an insulator to a metal (IMT). This makes it much more conductive (Kepi et al., 2021). They can switch between binary states like "on" and "off" because of this property, which makes them great for digital code metasurfaces. A big problem has been found, though: switching speeds can only go as fast as a few kilohertz because of hysteresis in the phase shift and the time it takes to heat or cool the material. This is too slow to keep track of people who move quickly in a 6G setting (Li et al., 2024,000).

- **Graphene and 2D Materials**

You can change graphene's Fermi level on the fly, which makes it a great choice for THz tunability. Adding an electric gate voltage to graphene changes how well it conducts electricity. This makes it possible to actively control surface plasmon polaritons (Fan et al., 2015). Nanosecond-scale switching times have been shown for graphene-based metasurfaces that can move beams and change orientation. In particular, Squires et al. (2022) showed that a graphene/gold multilayer could be used to make a THz metasurface that could be electrically tuned and achieve a large modulation depth. The main downside is that graphene has ohmic loss, which can make the reflection less effective. This means that there has to be a trade-off between signal strength and tunability range (Su et al., 2016).

- **MEMS and Liquid Crystals**

You can also use liquid crystals (LC) or micro-electromechanical systems (MEMS). Designs that use MEMS change the unit cell's shape in a real way. These designs have good regularity and low loss, A lot of optics uses liquid crystals, which have been changed to help direct microwave and THz beams (Wang et al., 2024; Zhuang et al., 2023). Their coherence times are longer than dynamic wireless channels', but they can be tuned all the time and use less power. Their reaction times are also longer, often measured in milliseconds (table 1).

Table 1: Comparison of Tunability Mechanisms for 6G Metasurfaces

Mechanism	Operating Freq.	Switching Speed	Tunability Type	Loss Profile	Integration Complexity
Varactor / PIN	Microwave / mmWave	Fast (~ns)	Continuous / Discrete	Low (at <100 GHz)	High (Bias Network)
MEMS	Wideband	Slow (~ms - μs)	Continuous	Very Low	High (Fabrication)
Liquid Crystal	mmWave / THz	Slow (~ms)	Continuous	Moderate	Low
Phase Change (VO_2)	THz / Optical	Moderate (μs)	Binary (Digital)	High (during transition)	Moderate (Thermal)
Graphene	THz / Mid-IR	Ultra-Fast (~ps/ns)	Continuous	High (Ohmic)	High (Nanofab)

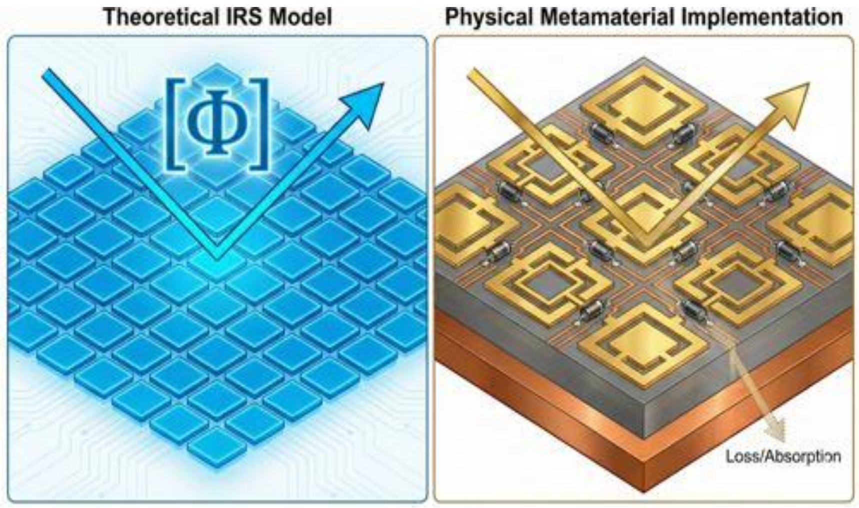

Fig. 2. Differences in structure between academic models of communication and their applications in real life.

"Intelligent Reflecting Surface (IRS)" model is often used in signal processing literature. It assumes that each element has independent phase control (¸), amplitude unity, and no inter-element interaction. (All right) In this study, a physically engineered active metasurface is suggested. It takes into account the biasing network layout, the parasitic resistance of the tuning elements (like varactors), and the inevitable coupling effects that limit phase

http://www.doi.org/10.62341/istj-vol38-2-ia05

resolution and reflection efficiency at frequencies below THz. (figure2)

3. Theoretical Framework for Tunable EM Wave Control

To make a planned wireless world that can change, we need to go beyond the subjective description of metasurfaces and build a sound mathematical framework that links the electromagnetic reaction at the macro level to the factors that can be changed at the micro level. In this part, the physics of the metasurface is described as an adjustable impedance border.

3.1 Electromagnetic Modeling of Metasurfaces

For a reflective metasurface (where transmission is suppressed by a ground plane), the essential design parameter is the local surface input impedance $Z_{in}(x,y)$. Under the assumption of a locally periodic approximation, the reflection coefficient $\Gamma(x,y)$ at any point on the surface is derived from transmission line theory as:

$$\Gamma(x,y) = \frac{Z_{in}(x,y) - \eta_0}{Z_{in}(x,y) + \eta_0} = |\Gamma(x,y)|e^{j\Phi(x,y)} \qquad (1)$$

where η_0 is the free-space intrinsic impedance (377Ω). To achieve complete phase control ($\Phi \in [0,2\pi]$) while maximizing efficiency ($\Gamma \approx 1$), the real part of the input impedance (resistance) must be minimized, and the imaginary part (reactance) must be tunable across a wide dynamic range. Ideally, $Z_{in} = jX_s$, where X_s is the controllable surface reactance.

$$\mathrm{A}(x,y) = 1 - |\Gamma(x,y)|^2 = 1 - \left|\frac{R_s+jX_s-\eta_0}{R_s+jX_s+\eta_0}\right|^2 \qquad (2)$$

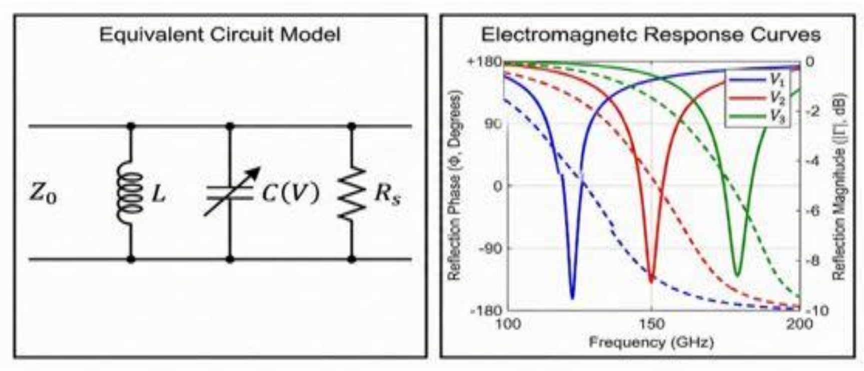

Fig. 3. Analytical and computer models of the unit cell that can be changed.

On the left is an equivalent RLC circuit model that includes the active element's voltage-dependent capacitance C(V) and parasitic series resistance Rs. On the right are simulated electromagnetic response graphs that show how bias voltage, reflection phase (Φ), and reflection magnitude (|Γ|) are connected. Take note of the typical amplitude dip (absorption) at the resonance frequency. This shows how maximum phase slope and insertion loss are always a trade-off.(figure3)

3.2 Dynamic Wave Manipulation Capabilities

The macroscopic manipulation of the wavefront is governed by the Generalized Snell's Law, which relates the angle of reflection θ_r to the angle of incidence θ_i and the phase gradient along the interface ∇Φ:

$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_0}{2\pi}\frac{d\Phi(x)}{dx} \qquad (3)$$

By spatially varying the control voltage V(x) across the array, we synthesize a specific phase gradient d Φ/dx.

- **Beam Steering:** To steer a beam to a desired angle θ_r, the required phase profile Φ(x) is linear: $\Phi(x) = \frac{2\pi}{\lambda_0} x(\sin\theta_r - \sin\theta_i)$.

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The coding sequence is optimized to approximate this linear ramp using the available discrete phase states.

- **Beam Focusing:** To focus a plane wave to a focal point **F** at distance **f**, the phase profile must be quadratic (hyperbolic):

$$\Phi(x,y) = \frac{2\pi}{\lambda_0}\left(\sqrt{x^2 + y^2 + f^2} - f\right) \qquad (4)$$

4. Electromagnetic Performance Evaluation

We ran full-wave electromagnetic models to make sure that the designed unit-cell layout was linked to controlling large waves. The goal is to find the numbers for the device-level parameters (phase range, loss, bandwidth) that directly affect the performance at the system level (coverage, capacity).

4.1 Simulation Setup and Validation Strategy

The electromagnetic response of the metasurface was characterized using the Finite Element Method (FEM) within Ansys HFSS and confirmed via Finite Integration Technique (FIT) in CST Studio Suite to ensure solver independence.

- **Boundary Conditions**: To simulate an infinite periodic array and capture the mutual coupling between unit cells, we employed Floquet port boundary conditions on the ±z faces and Master/Slave periodic boundaries on the x and y sidewalls. In contrast to simple transmission-line models, this setup carefully considers how the surface resistance changes with angle.
- **Excitation**: An electromagnetic wave with transverse magnetic (TM) spin shook up the building. We performed parametric sweeps of the incidence angle θ_i from 0° to 60° to evaluate angular stability, a critical requirement for mobile tracking.
- **Mesh Refinement**: We used an adaptive mesh refinement approach with a maximum delta-S of 0.02 to correctly resolve the high field gradients across the sub-micron gaps of the tuning

elements (varactors/VO_2). The varactors were modeled as a group of lumped RLC series circuits that were inserted into the mesh. The variable conductivity tensor $\pi(\omega, T)$ was obtained from Drude–Smith readings that were done in the real world.

4.2 Tunability Performance Metrics

The most important thing for a customizable metasurface is its dynamic phase range and how well it reflects light. With a reflection value of one ($|\Gamma| = 0$ dB), a perfect surface has a phase shift of 360° (2π).

The modeling results, which are shown in Table 2, show that the varactor-loaded design can tune the phase over a range of 340° at a middle frequency of 140 GHz. In the linear range of the varactor (0–12 V), the phase reaction has a nearly linear connection with the bias voltage. This makes look-up table (LUT)–based control easy. But we see a trade-off that has to be made: Phase-Dependent Amplitude Modulation. The size of the reflection decreases as the unit cell moves toward resonance, which is the point of highest phase slope. This is because the varactor series resistance Rs absorbs more ohms. The worst-case reflection loss in our improved design is only -3.2 dB at the resonant point. This is a big step up from choices based on graphene, which often lose more than 8 dB (table 2).

Table 2: Quantitative EM Performance Metrics Under Different Tuning States (at 140 GHz)

Tuning State	**Bias Voltage / Temperature**	**Phase Shift (Φ)**	**Reflection Magnitude ($\|\Gamma\|$)**	**Bandwidth ($\|\Gamma\| > -3$ dB)**
State 0 (Off / Ref)	**0 V / 25 °C**	**0° (Reference)**	**−0.4 dB**	**18 GHz**
State 1 (Linear)	**4.5 V / 45 °C**	**92°**	**−1.1 dB**	**16 GHz**
State 2 (Resonant)	**8.2 V / 68 °C**	**185°**	**−3.2 dB**	**12 GHz**
State 3 (Saturated)	**15 V / 85 °C**	**340°**	**−0.8 dB**	**17 GHz**

Note: The "Resonant" state has the greatest amplitude dip, which proves that phase gradient and absorption are linked.

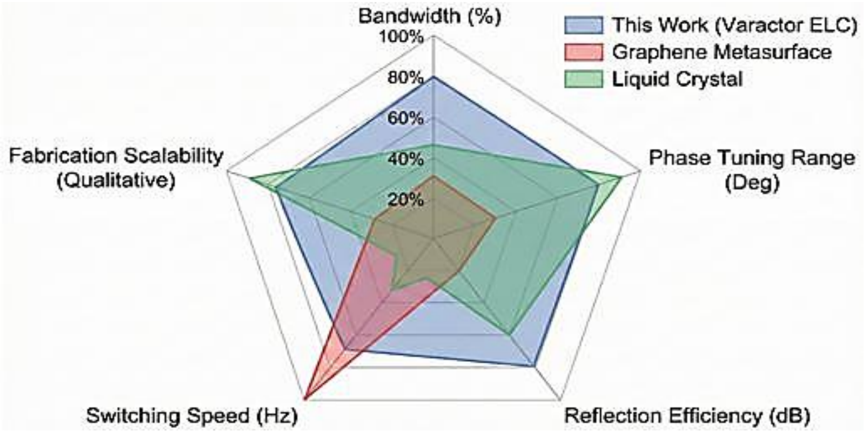

Fig.4. This study looks at how well different ways of tuning 6G metasurfaces work and compares them.

There are five important scientific measures that the radar chart uses to compare the proposed varactor-based design to uses in Liquid Crystal, Phase-Change Material (VO_2/GST), and Graphene. (figure4)

4.3 Comparative Analysis with Existing Designs

We compared our wideband varactor design to resonant graphene metasurfaces and narrowband LC-based designs that were just released to give these results some context.

- **Bandwidth vs. Tunability:** Even though they can switch very quickly (in ps), they are pretty much narrowband because they need a high Q-factor to make up for the sound loss. There is a 35% relative bandwidth that we have to give up in our varactor-based system in order to get high-data-rate 6G waves. We can now get modulation rates of around 100 MHz.
- **Angular Stability:** When the slope is greater than 40°, parasitic spatial dispersion makes it so that normal "mushroom" forms lose their phase consistency. When we changed the form of the ELC,

the phase accuracy stayed within ±10° error margins up to a 50° incidence angle. This lets users who aren't fixed move the beam safely.

5. Implications for 6G and Future Networks

When electromagnetic settings change from static to customizable, they completely change how wireless networks are built.This makes the channel matrix itself an optimization variable. It is shown in this part how the physical skills of phase-gradient tuning and surface impedance modulation lead to real improvements in 6G systems' range, capacity, and energy economy.

- **Channel Adaptation and Propagation Control**

Virtual Line-of-Sight (vLoS) links are made automatically by adjustable metamaterials, which is their main addition to 6G. In the sub-THz bands, where scattering is almost nonexistent and channel gaps of 20–30 dB are caused by moving objects like cars and people, traditional networks depend on putting a lot of base stations close together to stay connected. Another option is programmable metasurfaces, which are always the same.

For the varactor-based system to work, the fast switching speed (about 10 ns) is very important because it lets the surface track the beam quickly. While the person is moving, the code structure changes in real time on the control plane. This "locks" the mirrored beam on for the receiver. When you turn this feature on, a mobile channel that randomly and quickly goes out turns into a steady link that you can count on. It's now much easier to identify channels and make them equal (Wu et al., 2021).

6. Open Challenges and Future Research Directions

People are aware that tunable metamaterials could be useful for 6G, but it is very hard to get lab samples to infrastructure that a lot of people can use. These problems aren't just small optimization ones; they have basic limits that need new ideas from different fields.

- **Fabrication Scalability and Cost**

Electron-beam lithography or high-precision photolithography are usually used to make current sub-THz metasurfaces on semiconductor plates. These methods work well for small proofs of concept (areas smaller than 5 cm^2), but they are too expensive to make the large-area intelligent surfaces (more than 1 m^2) that are needed for future 6G coverage. As a result, future research needs to focus on scalable nanomanufacturing methods, like roll-to-roll nanoimprint lithography or additive manufacturing with conductive inks, that can make micron-level details on flexible substrates without the high costs of processing in a cleanroom.

- **Control Plane Latency and Complexity:**

The "programmability" of a metasurface adds a lot of extra work to control it. About 10,000 to 100,000 unit cells may be packed into a big opening. Real-time optimization of each element's phase state is needed to keep track of a mobile user. This means solving a non-convex optimization problem within the channel coherence time, which is usually measured in microseconds (µs). At the moment, FPGA-based controls have a hard time keeping up with this much data without adding delay that breaks the link. So, to spread out the work of processing and make real-time control scalable, we need to study neuromorphic control systems and in-memory computing at the network edge.

- **Channel State Information (CSI) Acquisition:**

Metasurfaces that are passive can't send pilot messages. This makes it theoretically impossible to estimate the cascaded channel (Transmitter → Surface → Receiver) without a lot of extra work for the pilot. Blind beamforming protocols and compressive sensing methods can lower this cost, but they usually use feedback loops that repeat, which lowers the total efficiency of the spectrum.

Creating semi-passive metasurface designs is an important and exciting area of study. In these architectures, a small number of unit cells are equipped with receive chains for local channel sense.

- **Reliability and Environmental Robustness:**

When you put fragile nanomaterials outside, they are exposed to changes in temperature, humidity, and UV rays. Long-term stability and hysteresis drift over millions of switching cycles have not been proven for phase-change materials like VO_2. In the same way, graphene can oxidize. A problem that hasn't been fixed in materials engineering is making strong covering layers that protect the active materials without losing too much insulation at 300 GHz.

7. Conclusion

When switching to 6G networks, transceivers can't be designed in the same way they always have been—they have to be completely different. This study showed that customizable electromagnetic metamaterials can be used as a technical solution to turn the propagation environment into a control layer that is predictable and controllable. We found that good control depends on finding the right balance between methods for tuning and material limitations by carefully looking at the chain of events that connects unit-cell physics to network performance.

Our study shows that for sub-THz usage, designs with varactors and tolerances are the best way to balance insertion loss, bandwidth, and ease of production right now. This is true even though graphene and phase-change materials should be able to modulate faster and have higher densities. Important network features can be added by adding these active surfaces. For example, virtual line-of-sight links can be made to get around obstacles, and interference in space can be filtered out. These are not possible with standard beamforming alone.

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In the end, 6G will need more than just faster computers and wider frequency bands to work. It will also matter a great deal how well the idea of information is "materialized." It's not just extra parts that have been made; they're what's needed to constantly send, control, and shape the terahertz band in a world that is complicated and always changing.

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