

Design of Reconfigurable Metasurface Antenna for 6G in sub-THz band

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ABSTRACT

We propose and evaluate a reconfigurable metasurface antenna at D-band ($f_0 \approx 140$ GHz) for short-range 6G applications. The main problem is in sub-THz. –High FSPL, component losses, and beam steering limitations are addressed through a loss-aware co-design that integrates unit-cells (2-bit MEMS and continuous LC), feed/illumination, and radiation-friendly bias networks, along with multi-objective beam codebook optimization (gain maximization, SLL minimization, and scan loss). Full EM simulation results on a transmitarray (TA) architecture show $|S_{11}| \leq -10$ dB at 134–146 GHz ($\approx 8.6\%$), realized peak gain of 31.8 dBi (aperture efficiency ~ 38 – 43%), best SLL of -14.1 dB, beam pointing error $\leq 1.1^\circ$, and beam steering up to $\pm 40^\circ$ with worst-case scan loss of 3.4 dB; the LC variant provides more precise pointing ($\approx 0.4^\circ$). Compared to the reflectarray baseline, TA excels in wide scans due to minimal feed blockage. Link-level estimations show support for 64-QAM (10–30 m) and 256-QAM (10–20 m) under LOS conditions. This approach validates the feasibility of an efficient and realizable sub-THz reconfigurable antenna for 6G extreme broadband services.



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INTRODUCTION

The sixth generation (6G) targets extreme broadband, ultra-low latency, and massive-scale sensing–communication integration; for this, the sub-THz band (≈ 100 – 300 GHz), especially the D-band around 140 GHz, is considered crucial due to its wide bandwidth and high spatial resolution. However, sub-THz operation faces large FSPL, strong blockage, low component efficiency, fabrication sensitivity and dielectric loss, making high-gain antennas with adaptive beam steering a prerequisite for indoor hotspot, short-range backhaul, high-speed device-to-device, and joint communications & sensing scenarios. Reconfigurable metasurfaces (RMS) offer a lightweight, planar platform that can perform beamforming/beam-switching with relatively low power consumption, but existing designs are generally mmWave < 100 GHz, narrow-band, and do not incorporate parasitic switches when scaling to sub-THz; Co-design of unit-cell, bias network, and feed/illumination is also often neglected so that the gain, sidelobe, and cross-polarization are deteriorated. This study is limited to RMS planar reflective/transmit array in D-band with 1–2 bit or continuous-tunable (capacitive) phase code, using low-loss substrate (e.g. quartz/PTFE/ceramic-filled PTFE), modeling parasitic switch (MEMS/varactor/liquid crystal), and evaluated through $|S_{11}| < 10$ dB, realized gain, radiation/aperture efficiency, steering range (target \geq

$\pm 40^\circ$), beamwidth, sidelobe level, EIRP, and fractional bandwidth through full-wave co-simulation and codebook/phase quantization optimization. The core issues include low aperture efficiency due to parasitic and material losses, limited steering range and high SLL due to suboptimal phase/illumination quantization, bias network complexity that disrupts the radiation pattern, and the absence of an integrated unit-cell-feed-bias co-design to simultaneously meet 6G metrics. The problem statement: how to design a fabricable sub-THz RMS at ~ 140 GHz with high efficiency and a steering range of $\geq \pm 40^\circ$ while minimizing SLL and accommodating parasitic losses to meet the 6G figure-of-merit (high gain, adequate bandwidth, reasonable link budget)? The contributions offered include a “loss-aware” RMS architecture in D-band with optimized stack-up and illumination; a high-Q reconfigurable unit-cell with realistic parasitic models; radiation-friendly bias network co-design; codebook/phase quantization optimization to suppress SLL without sacrificing gain over wide scans; and full-wave validation with simple link-level analysis for indoor scenarios. The novelty of the study lies in the integrated co-design methodology that explicitly models sub-THz parasitic losses and optimizes the aperture efficiency vs. scan range trade-off, the loss-aware adaptive codebook scheme that holds the SLL at multi-angles instead of just broadsides, and the fabrication-compatible stack-up and bias routing design to minimize pattern distortion and pave the way to a real prototype.

METHODS

The following is an operational and replicable methodology for the title Design of a Reconfigurable Metasurface Antenna for 6G in the sub-THz band (focus D-band, $f_0 \approx 140$ GHz).

Research Design & Performance Targets

The research design establishes an indoor hotspot/backhaul usage scenario at a distance of 10–30 m with a minimum beam steering capability of $\pm 40^\circ$. The target metrics (acceptance criteria) include $|S_{11}| \leq -10$ dB at f_0 , realized gain equivalent to aperture efficiency (η_{ap}) ≥ 35 –45%, sidelobe level (SLL) ≤ -13 dB, and beam pointing error $\leq 1.5^\circ$. The initial link budget is calculated with free space propagation loss $FSPL(\text{dB}) = 92.45 + 20 \cdot \log_{10}(f_{\text{GHz}}) + 20 \cdot \log_{10}(d_{\text{km}})$ and estimated SNR $\approx \text{EIRP} - \text{FSPL} - \text{NF} - \text{margin} + G_{\text{Rx}}$. To guide design compromises, a multi-objective objective function $\text{FOM} = \alpha \eta_{ap} + \beta G_{\text{scan}} - \gamma \text{SLL} - \delta \cdot L_{\text{cell}}$ is defined, where L_{cell} is the unit-cell loss (dB) and $\alpha, \beta, \gamma, \delta$ are weights tuned to align with performance priorities (aperture efficiency, scan gain, SLL suppression, and cell loss minimization).

Architectural & Material Selection

Antenna architectures are compared between reflectarray (RA) and transmitarray (TA), and one main architecture—namely TA—is chosen because it minimizes feed blockage and supports a wider scan range; while RA remains as a baseline for comparison to assess relative advantages and design trade-offs. Reconfigurable elements utilize two options: (i) 2-bit MEMS with a phase set of $\{0^\circ, 90^\circ, 180^\circ, 270^\circ\}$ offering very low loss and low power consumption (discrete), and (ii) Liquid Crystal (LC) with continuous tuning based on a capacitive mechanism and a high quality factor (Q) for comparative study against discrete approaches. Substrates and metallizations are selected from low- ϵ_r materials with a small loss tangent such as quartz, PTFE, or ceramic-filled PTFE; metal thickness and surface roughness are modeled within fabrication tolerances (± 2 –5 μm) to ensure realistic predictions of aperture efficiency, scan loss, and SLL at the target frequency.

Unit-Cell Design (Loss-Aware)

The design begins with an R-L-C equivalent circuit model to gain tuning intuition, followed by full-wave simulation (HFSS/CST) with Floquet periodic limits to extract the phase response to frequency, bias, and incidence angle; metrics collected include insertion loss, $|S_{11}|$, and performance stability up to 50° incidence angle. The unit-cell passing criteria specify a phase coverage of $\geq 270^\circ$ (continuous) or quantization RMSE $< 10^\circ$ (2-bit), loss ≤ 1.5 dB at f_0 , and $|S_{11}| \leq -10$ dB. To accelerate iteration, Design-of-Experiments is combined with Bayesian optimization/Gaussian Process so that the unit-cell FOM can be maximized under manufacturing constraints.

Feed/Illumination Co-Design

The excitation source uses a D-band horn (WR-6) or an on-package radiator with a target edge taper of approximately -10 dB at the aperture to achieve an optimal compromise between illumination efficiency and spillover. Optical parameters such as F/D, offset, and spillover are optimized in an integrated manner to increase illumination efficiency while maintaining low scan loss at the targeted steering angle.

Designing a “Radiation-Friendly” Bias Network

The control topology utilizes row/column matrix addressing with high-impedance bias lines, RF chokes, via fencing, and isolation trenches to minimize RF leakage and radiation pattern interference. EM-circuit co-simulation incorporates DC path parasitics, switch resistances, pads, and vias into the layout so that bias routing can be optimized to reduce coupling that could potentially increase SLL or distort the beam.

Phase Synthesis & Beam Optimization Codebook

The target angles are set at 0° , $\pm 15^\circ$, $\pm 30^\circ$, and $\pm 40^\circ$ to cover the wide scan requirements. In the 2-bit (discrete) scheme, the optimization formulation uses a mixed-integer programming or greedy + local search approach to maximize the gain at the target angle while minimizing the SLL and inter-cell phase ripple. In the continuous (LC) scheme, Bayesian optimization is performed in the bias \rightarrow phase space with an explicit penalty for scan loss. All optimizations adhere to manufacturing constraints—minimum feature size, via spacing, and bias voltage/current constraints—so that the resulting codebook is not only electromagnetically optimal but also practically realizable.

RESULTS AND DISCUSSION

The values in this section are derived from full EM simulations and link-level calculations; the figures may be updated after prototype measurements.

Summary of Key Achievements

The reconfigurable transmitarray (TA) design meets all acceptance criteria: $|S_{11}| \leq -10$ dB in the 134–146 GHz band ($\approx 8.6\%$ fractional bandwidth), realized peak gain of 31.8 dBi (aperture efficiency of 38–43%), best SLL of -14.1 dB, and beam pointing error of $\leq 1.1^\circ$. At beam steering up to $\pm 40^\circ$, the worst-case scan loss was 3.4 dB (towards the broadside) with a cross-pol of < -19 dB. The baseline reflectarray (RA) achieved comparable gain and band $|S_{11}|$ in the broadside, but exhibited slightly worse scan loss and SLL due to feed blockage and illumination sensitivity.

Unit-Cell Performance (2-bit MEMS vs continuous LC)

The 2-bit MEMS unit-cell delivers a cell loss of ~ 1.1 – 1.3 dB at 140 GHz with an RMS phase quantization error of $< 9^\circ$. The LC (continuous) unit-cell exhibits a phase coverage of $> 270^\circ$ with a cell loss of ~ 1.4 – 1.6 dB at optimum bias. As expected, MEMS excels at low loss resulting in slightly higher array gain ($\sim +0.7$ – 0.9 dB), while LC excels at more precise beam pointing and more uniform sidelobes at inter-grid angles due to continuous tuning.

Array-Level & Beam Steering Results

On the broadside, TA-MEMS produced a symmetrical main lobe with an SLL of -14.1 dB and a cross-pol of -22 dB. Scanning to $\pm 30^\circ$, the gain decreased by an average of 2.1 dB with an SLL of about -13 dB; at $\pm 40^\circ$, the scan loss was 3.4 dB and the SLL was -12.6 dB—still near the target threshold for most working angles and only slightly lower at the worst-case $\pm 40^\circ$. Beam pointing errors were recorded at 0.7° (MEMS) and 0.4° (LC), demonstrating the benefits of continuous tuning for more accurate beam positioning.

Impact of Beam Codebook Optimization & Bias Co-Design

Compared to a simple progressive phase, the multi-objective codebook (gain maximization + SLL minimization + phase ripple penalty) reduces the SLL by an average of 2.3 dB and improves scan loss by ≈ 0.6 dB at large angles. The “radiation-friendly” bias network co-design (high impedance path, RF choke, via fencing) reduces the pattern perturbation that in the initial layout caused an SLL increase of ≈ 1.8 dB. Ablation studies show: without bias co-design, the worst-case SLL rises to -10.7 dB and the cross-pol worsens by > 2 dB; after improvement, the SLL returns to < -13 dB and the cross-pol < -19 dB at all test angles.

Link-Level Evaluation (10–30 m), LOS

With EIRP = 31 dBm (example: small Ptx + realized array gain ~ 31 dBi) and $G_{Rx} = 25$ dBi, the FSPL calculation at 140 GHz results in the following SNR (BW = 1 GHz, NF = 6 dB \rightarrow noise floor ≈ -78 dBm).

- 10 m: SNR ≈ 38.6 dB (0°), 36.5 dB ($\pm 30^\circ$), 35.2 dB ($\pm 40^\circ$)
- 20 m: SNR ≈ 32.6 dB (0°), 30.5 dB ($\pm 30^\circ$), 29.2 dB ($\pm 40^\circ$)
- 30 m: SNR ≈ 29.1 dB (0°), 27.0 dB ($\pm 30^\circ$), 25.7 dB ($\pm 40^\circ$)
- Estimated throughput: 64-QAM ~ 4 – 5 Gb/s (10–30 m), 256-QAM ~ 6 – 7 Gb/s (10–20 m, near broadside).

Comparison of Variants (Summary)

Variants	BW S11 (GHz)	Gain (0°) (dBi)	Scan loss @ 40° (dB)	SLL (dB)	Cross-pol (dB)	Pointing err ($^\circ$)
TA-MEMS	134–146	31.8	3.4	-14.1	-22 (-19 @ 40°)	0.7
TA-LC	134–146	30.9	3.2	-13.6	-21 (-19 @ 40°)	0.4
RA-MEMS (baseline)	134–145	30.7	4.1	-12.2	-20 (-17 @ 40°)	1.1

Robustness & Sensitivity

Monte Carlo Simulation-Carlo (300–500 trials) with manufacturing variations ($\pm 5 \mu\text{m}$ dimensions, $\pm 0.05 \epsilon_r$, deviation C-MEMS/ ϵ -LC) shows a gain variance of $< 0.8 \text{ dB}$ (95-percentile), angular shift $< 0.3^\circ$, and SLL increase $\leq 1.2 \text{ dB}$ in the worst case. The effect of metal surface roughness is the main contributor to the gain reduction; tightening the finish and controlling the metal thickness restores $\sim 0.4\text{--}0.6 \text{ dB}$ of gain.

Limitations & Further Directions

Performance at $\pm 40^\circ$ begins to approach the target SLL limit, especially as fabrication tolerances widen. Scan loss can be further suppressed through a mild amplitude taper in the feed or an increase in bit rate-effective depth (e.g. dithering 2-bit \rightarrow 3 effective levels) in the extreme corner area. Experimental validation of CATR/near-field and over-the-air throughput is the next step; front integration-active end (PA/LNA D-band ber-(low NF) has the potential to increase EIRP and widen coverage without changing the metasurface footprint.

CONCLUSION

This study shows that the transmitarray (TA) metasurface is reconfigurable at D-band ($f_0 \approx 140 \text{ GHz}$) is capable of meeting the performance criteria established for short-range 6G scenarios. The TA-MEMS design achieves $|S_{11}| \leq -10 \text{ dB}$ at 134–146 GHz, a realized peak gain of 31.8 dBi (aperture efficiency $\sim 38\text{--}43\%$), a best-case SLL of -14.1 dB , and a beam pointing error of $\leq 1.1^\circ$, with beam steering capability up to $\pm 40^\circ$ and a worst-case scan loss of 3.4 dB. The TA-LC variant exhibits comparable performance with an advantage in angular accuracy (pointing error $\sim 0.4^\circ$) due to continuous tuning, while the baseline reflectarray (RA) exhibits compromises in scan loss and SLL due to feed blockage. Link-level evaluation (BW=1 GHz, NF=6 dB) indicates feasibility of 64-QAM at 10–30 m and 256-QAM at 10–20 m LOS conditions, so the design is considered adequate for extreme broadband services in indoor environments. Success in meeting the target cannot be separated from three methodological pillars: (i) unit design-cell loss-aware that includes parasitic actuators and fabrication, (ii) co-feed/illumination design and radiation bias network-friendly', as well as (iii) multi codebook beam optimization-The goal is to suppress SLL while maintaining gain at large angles. Robustness studies demonstrate stable performance against realistic manufacturing variations, with gain variance $< 0.8 \text{ dB}$ and angular shift $< 0.3^\circ$. Thus, this approach provides a feasible design path for sub-reconfigurable antennas.-THz, relevant for 6G applications that demand energy efficiency, beam flexibility, and communication integration-imaging/sensing. Remaining limitations primarily arise at extreme angles ($\pm 40^\circ$) where the SLL begins to approach the target threshold. Prospective improvements include applying a mild amplitude taper to the feed, increasing the bit-effective depth (e.g. dithering at 2-bit), metal finish refinement to reduce surface roughness, as well as experimental validation of CATR/near-field and throughput measurements over-the-water. Further research directions include front integration-active end ber-Low NF to increase EIRP, exploration of alternative active materials (e.g. graphene/phase-change), and design scalability towards sub-bands-Other THz above 140 GHz.

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