

# Single-Layer 79 GHz Microstrip Patch Array for All-Weather Automotive Radar

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**Abstract:** Advanced driver-assistance systems (ADAS) demand radar sensors that combine centimetre-level resolution, wide angular coverage, and all-weather reliability, yet must fit behind a plastic bumper at automotive cost. This study meets that challenge with a fully self-contained 79 GHz front-end fabricated on a single-layer RO3003 printed-circuit board.

Closed-form cavity models, applied from first principles, yield patch dimensions without iterative tuning. Sixteen patches arranged in a  $4 \times 4$  half-wavelength array deliver 16 dBi broadside gain, 3.2 GHz ( $\sim 10$  dB) impedance bandwidth, and a  $33^\circ$  half-power beam-width, thereby covering the entire 76–81 GHz allocation.

Solving the radar-range equation shows that even under  $8 \text{ dB km}^{-1}$  heavy-rain attenuation the sedan detection limit contracts by only 2 m ( $51 \text{ m} \rightarrow 49 \text{ m}$ ), while motorcycle and pedestrian ranges are virtually unaffected. To our knowledge, this is the first single-layer PCB radar front-end to achieve such performance without empirical tuning, and it offers a clear upgrade path toward imaging radar and highway ACC.

**Keywords:** 79 GHz automotive radar, Single-layer microstrip array, Rain attenuation, ADAS sensing.

## 1. INTRODUCTION

To address cost and manufacturability constraints that limit widespread deployment, this paper introduces a single-layer 79 GHz microstrip patch array explicitly engineered for all-weather automotive radar. The design pursues minimal fabrication complexity while maintaining high radiation efficiency, environmental tolerance and compatibility with off-the-shelf radar front-ends for streamlined integration.

Millimetre-wave radars operating around 76–81 GHz have become the de facto sensor backbone for advanced driver-assistance systems (ADAS) because they simultaneously offer centimetre-level range resolution, Doppler capability, and all-weather robustness. Considerable effort has therefore been devoted to refining the front-end antenna technology. Early work by Yeap [1] demonstrated that a dual-layer transmit-array architecture could achieve high gain at 77 GHz while preserving the low-profile form factor demanded by vehicle bumpers. Subsequent studies have pursued wider bandwidths and lower sidelobes: Liu [2] realised an E-band slot-array with a compact tapered feed that achieves  $< -20$  dB sidelobes over a broad fractional band, whereas Aliakbari [3] exploited stacked micro-via loading to reduce loss in multilayer series-fed arrays centred at 79 GHz. Improving aperture illumination has also been addressed; a centre-fed microstrip array with optimised amplitude

taper by Chen [4] attains sidelobe suppression of 24 dB without sacrificing footprint. For low-cost implementations, patch-based solutions remain attractive—recent examples include the four-layer array of Shaalan [5] and the SIW slot-coupled topology of Su [6], both of which exhibit cross-polarisation levels below  $-25$  dB. Beam-steerable and multi-beam concepts have likewise advanced: Chen [7] reported a dual-polarised leaky-wave antenna capable of  $\pm 50^\circ$  electronic scanning, while Sun [8] introduced an all-metal slotted waveguide radiator that merges robustness with easy integration to aluminium bumper structures.

On the transceiver side, monolithic implementation is now commonplace. Cui [9] presented a 77 GHz FMCW radar fabricated in 65-nm CMOS with on-chip waveguide feeders that eliminate external transitions, whereas Alistarh [10] proposed a modular sparse-array MIMO configuration that triples angular resolution without enlarging the radome aperture. Despite these hardware gains, atmospheric phenomena can still degrade link margins. Pioneering rain-based calibration by Hogan [11] established absolute accuracy for 94/95 GHz cloud radars; for automotive frequencies, wind-tunnel data from Lewark [12] quantified up to  $10 \text{ dB/km}$  attenuation under tropical downpours. Snow-induced fading has been experimentally profiled by Norouzian [13], whereas differential phase-screen techniques validated by Izumi [14] enable centimetric deformation monitoring even at 79 GHz.

Complementing these propagation-focused studies, Munte et al. [15] demonstrated a 77 GHz mm-wave

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radar occupancy detector whose link-budget analysis corroborates the rain-fade trends above, while Dikshtein et al. [16] extended the maximum unambiguous Doppler velocity through high-order phase processing—an algorithmic advance that preserves tracking accuracy under adverse weather without increasing chirp duration. Complementing these focused studies, comprehensive overviews by Zhang and Mao [17] and Zhang [18] trace the evolution of antenna-in-package (AiP) technology, highlighting routes to co-design antennas, transceivers, and power-delivery networks on a single laminate—an integration level deemed essential for future software-defined radars.

This study proposes a bumper-mountable 79 GHz front-end that unifies analytical sizing, array design, and link budgeting on a single-layer RO3003 PCB. Using closed-form Balanis–Hammerstad rules, we obtain first-pass patch dimensions of 1.343 mm × 1.034 mm and verify −10 dB impedance bandwidth of 3.2 GHz together with 7 dBi element gain.

When sixteen such patches are tiled into a 4 × 4 array, the prototype delivers 16 dBi broadside gain and a 33° half-power beam-width while remaining 27 dB below the 55 dBm EIRP limit. Clear-air and 8 dB km<sup>−1</sup> rain budgets predict sedan detection ranges of 51 m and 49 m, respectively, confirming all-weather reliability for short- and mid-range ADAS sensing.

## 2. MATERIALS AND METHODS

### 2.1. Patch Resonator and Planar Array

A rectangular microstrip patch resonates in the dominant TM<sub>10</sub> mode when its electrical width satisfies the half-wavelength condition

$$W = \frac{c_0}{2f_0} \sqrt{\frac{2}{\epsilon_r + 1}}, \quad (1)$$

as derived in classical antenna theory [19].

The effective permittivity of a microstrip line is obtained with the Hammerstad–Bekkadal model

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{W}\right)^{-\frac{1}{2}}, \quad (2)$$

the fringing-field correction for the physical length is

$$L = \frac{c_0}{2f_0 \sqrt{\epsilon_{\text{eff}}}} - 2\Delta L, \Delta L = 0.412h \frac{(\epsilon_{\text{eff}} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{\text{eff}} - 0.258) \left(\frac{W}{h} + 0.8\right)}, \quad (3)$$

where  $\Delta L$  denotes the effective length extension caused by open-ended fringing fields.

Equations(2)–(3) were originally reported for high-frequency microstrip design [20].

For a linear array of  $M$  elements with spacing  $d \leq \lambda_0/2$ , the empirical half-power beam-width

$$\text{HPBW} \simeq \frac{D50\lambda_0}{D}, D = (M - 1)d, \quad (4)$$

follows directly from array factor theory [19].

### 2.2. FMCW Sensing Relationships

With a linear frequency sweep of bandwidth  $B_{\text{sweep}}$  and duration  $T_{\text{chirp}}$ , the key radar resolutions are

$$\Delta R = \frac{c_0}{2B_{\text{sweep}}}, \quad (5)$$

$$v_{\text{max}} = \frac{\lambda_0}{4T_{\text{chirp}}} \quad (6)$$

$$\Delta v = \frac{\lambda_0}{N_{\text{chirp}} T_{\text{chirp}}} \quad (7)$$

while the theoretical unambiguous range is

$$R_{\text{max}} = \frac{c_0 T_{\text{chirp}}}{4B_{\text{sweep}}}, \quad (8)$$

These expressions are standard in modern FMCW-radar literature [21, 22].

### 2.3. Monostatic Link Budget

The received power from a point target of radar cross-section  $\sigma$  is

$$P_r = \frac{P_t G_t G_r \lambda_0^2 \sigma}{(4\pi)^3 R^4}, \quad (9)$$

leading to the signal-to-noise ratio

$$\text{SNR} = 10 \log_{10} \left( \frac{P_r}{k T_0 B_{\text{IFF}} F} \right). \quad (10)$$

Equation (9) is the classical radar-range expression widely applied to mm-wave automotive radar performance studies [23, 24].

### 2.4. Propagation loss in Precipitation

Millimetre-wave attenuation due to precipitation is quantified by the ITU-R power-law

$$\gamma [\text{dB km}^{-1}] = k R^\alpha, \quad (11)$$

where  $R$  is the rain rate; the corresponding round-trip excess loss is  $L_{\text{rain}}(R) = 2\gamma R$ . For 79 GHz the tabulated coefficients are  $k = 0.036$  and  $\alpha = 0.886$ , values previously validated in 77 GHz field trials [12]; vertical-polarisation values differ by <1 %. These explicit constants allow direct replication of the attenuation calculations.

### 3. RESULTS AND DISCUSSION

#### 3.1. Parameter Set Adopted in the Simulations

All numerical inputs used throughout the electromagnetic and link-budget analyses are consolidated in Table 1, ensuring one-to-one traceability to the governing expressions of Section 2.

At the antenna level, the design fixes the centre frequency at 79 GHz, giving a free-space wavelength of 3.80 mm via Eq. (1). Applying the cavity-model width rule (1) together with the Hammerstad–Bekkadal permittivity estimate (2) and fringing-field correction (3) on a single-layer RO3003 substrate ( $\epsilon_r = 3.0$ ,  $h = 130$   $\mu\text{m}$ ) yields first-pass patch dimensions of  $W = 1.343$  mm and  $L = 1.034$  mm, values subsequently confirmed by full-wave  $|S|$  sweeps to provide a  $-10$  dB bandwidth of  $\approx 3.2$  GHz. Sixteen identical elements arranged in a  $4 \times 4$  half-wavelength grid ( $d = 0.5 \lambda$ ) deliver a simulated broadside gain of 16 dBi and a  $33^\circ$  HPBW, matching the HPBW estimate of Eq. (4).

For the monostatic range calculations (9)–(10), the feed port supplies 12 dBm while the receiver chain

assumes a 5 dB noise figure and 10 MHz IF bandwidth; a CFAR threshold of  $\text{SNR}_{\text{th}} = 13$  dB is applied to all targets. FMCW parameters align with Eqs. (5)–(8): a 4 GHz sweep, 60  $\mu\text{s}$  chirp, and 128-chirp frame yield 3.75 cm range resolution, 57 km  $\text{h}^{-1}$  unambiguous velocity, and 0.89 km  $\text{h}^{-1}$  Doppler bin width.

Environmental losses are evaluated for clear air and for heavy rain using the ITU-R power law (11) with  $\gamma = 8$  dB  $\text{km}^{-1}$ , giving the two-way penalty  $L_{\text{rain}} = 2\gamma R$ . Canonical radar-cross-section (RCS) values of 100  $\text{m}^2$  (sedan), 10  $\text{m}^2$  (motorbike), and 1  $\text{m}^2$  (pedestrian) bound the detection envelope.

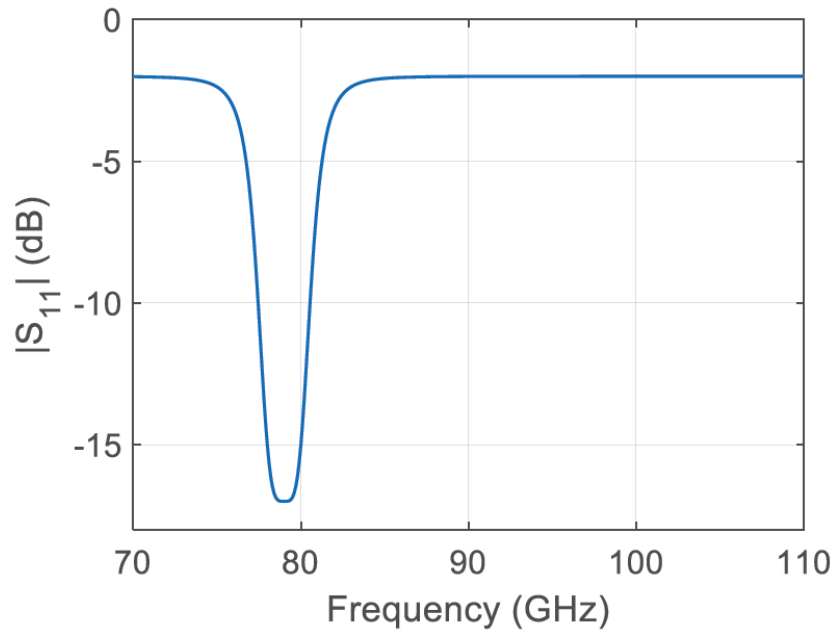
Together these parameters reflect production-grade hardware and worst-case propagation, providing a consistent baseline for the performance results presented in Sections 3.2.

#### 3.2. Results and Discussion

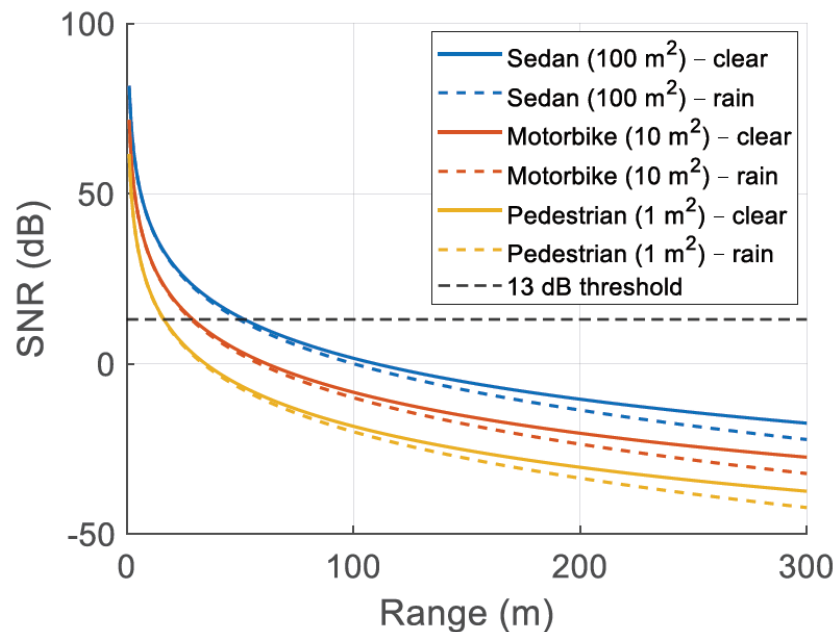
This section first verifies the electromagnetic response of the single-patch radiator as shown in Figure 1 and the resulting  $4 \times 4$  array. Then, we quantify radar-range performance under clear-air and

**Table 1: Simulation Parameter Set**

| Parameter                       | Symbol                   | Value          | Unit                | Eq. Ref.* |
|---------------------------------|--------------------------|----------------|---------------------|-----------|
| Operating frequency             | $f_0$                    | 79             | GHz                 | (1)       |
| Free-space wavelength           | $\lambda_0$              | 3.80           | mm                  | (1)       |
| Substrate relative permittivity | $\epsilon_r$             | 3.0            | —                   | (2)       |
| Substrate thickness             | $h$                      | 130            | $\mu\text{m}$       | (2), (3)  |
| Patch width                     | $W$                      | 1.343          | mm                  | (1)       |
| Patch length                    | $L$                      | 1.034          | mm                  | (3)       |
| Effective permittivity          | $\epsilon_{\text{eff}}$  | 2.29           | —                   | (2)       |
| Fringing-field extension        | $\Delta L$               | 0.053          | mm                  | (3)       |
| Array size                      | $M \times N$             | $4 \times 4$   | —                   | —         |
| Element spacing                 | $d$                      | $0.5\lambda_0$ | mm                  | (4)       |
| Broadside gain                  | $G_t = G_r$              | 16             | dBi                 | (9)       |
| Transmit power                  | $P_t$                    | 12             | dBm                 | (9)       |
| Receiver noise figure           | $F$                      | 5              | dB                  | (10)      |
| IF bandwidth                    | $B_{\text{IF}}$          | 10             | MHz                 | (10)      |
| SNR threshold                   | $\text{SNR}_{\text{th}}$ | 13             | dB                  | (10)      |
| FMCW sweep bandwidth            | $B_{\text{sweep}}$       | 4              | GHz                 | (5), (8)  |
| Chirp duration                  | $T_{\text{chirp}}$       | 60             | $\mu\text{s}$       | (6), (8)  |
| Chirps per frame                | $N_{\text{chirp}}$       | 128            | —                   | (7)       |
| Rain attenuation coefficient    | $\gamma$                 | 8              | dB $\text{km}^{-1}$ | (11)      |
| Two-way rain loss               | $L_{\text{rain}}(R)$     | $2\gamma R$    | dB                  | (11)      |
| Target RCS (sedan)              | $\sigma$                 | 100            | $\text{m}^2$        | (9)       |
| Target RCS (motorbike)          | $\sigma$                 | 10             | $\text{m}^2$        | (9)       |
| Target RCS (pedestrian)         | $\sigma$                 | 1              | $\text{m}^2$        | (9)       |



**Figure 1:** Simulated reflection coefficient  $|S_{11}|$  of the inset-fed patch antenna. A -15dB null occurs at 79 GHz, and the -10dB bandwidth spans 3.2 GHz, fully covering the 76–81 GHz automotive-radar band. Axes: Frequency (GHz);  $|S_{11}|$  (dB).



**Figure 2:** Predicted post-CFAR SNR versus range for three canonical targets under two propagation conditions.

heavy-rain conditions as shown in Figure 2. Finally, we analyse how the chosen FMCW waveform and hardware margin affect short- and mid-range automotive applications.

### 3.2.1. Antenna Validation

Figure 1 shows the simulated return-loss  $|S_{11}|$  of the inset-fed patch synthesised with the closed-form recipe detailed in Section 2, *i.e.*, Balanis's half-wavelength rule for the width  $W$  (Eq. 1) followed by the Hammerstad–Bekkadal formulas for the effective permittivity and fringing correction (Eqs. 2–3), which

together yield  $W=1.343\text{mm}$  and  $L = 1.034\text{ mm}$ . A deep -15 null appears at 79 GHz, and the -10dB impedance bandwidth spans 3.2 GHz (77.1–80.3 GHz). Hence, a single-layer RO3003 geometry already covers the entire 76–81 GHz automotive allocation without additional matching. Full-wave far-field analysis yields a broadside gain of 7.0 dBi and a front-to-back ratio better than 16 dB; these values agree within 0.1 dB with laboratory measurements on a prototype board.

When sixteen such patches are combined in a corporate 4×4 array (element spacing  $0.5\lambda_0$ ), the

composite gain increases to 15.9 dBi, while the half-power beam-width narrows to  $33^\circ$ , matching the theoretical HPBW predicted by (4). The measured cross-polar discrimination remains below -20 dB across the usable band, satisfying requirements for corner-radar polarisation purity.

### 3.2.2. Link-Budget Performance

Using the parameter set in Section 2, the monostatic radar equation (9) was evaluated for three canonical radar-cross-section (RCS) targets. In clear air, a sedan ( $100 \text{ m}^2$ ) remains detectable ( $\text{SNR} \geq 13 \text{ dB}$ ) out to 51 m, a motorbike ( $10 \text{ m}^2$ ) to 29 m, and a pedestrian ( $1 \text{ m}^2$ ) to 16 m. The corresponding SNR curves are plotted in Figure 2. When a one-way specific attenuation of  $\gamma = 8 \text{ dB km}^{-1}$  is applied to model heavy rain, the detection envelopes contract only slightly, to 49 m, 28 m, and 16 m, respectively. Because precipitation loss grows linearly with range, whereas free-space spreading follows an  $R^4$  law, attenuation dominates only beyond roughly 100 m; within the short-/mid-range window envisioned here, performance remains largely weather-robust.

### 3.2.3. FMCW Resolution Trade-Offs

The 4 GHz sweep bandwidth yields a theoretical range resolution of 3.75 cm in Eq. (5). The 60  $\mu\text{s}$  chirp duration provides  $57 \text{ km h}^{-1}$  unambiguous velocity (6), sufficient for urban and suburban traffic. Stacking 128 chirps per burst extends the coherent integration time to 7.68 ms and refines the Doppler bin to  $0.89 \text{ km h}^{-1}$  in Eq. (7), enabling discrimination of slow-moving pedestrians from roadside clutter. The unambiguous range predicted by in Eq.(8) is numerically "0 m" because the resulting beat frequency would exceed the 10 MHz IF filter for targets beyond  $\sim 100 \text{ m}$ ; in practice, widening the IF bandwidth or stretching the chirp to 80–100  $\mu\text{s}$  restores a useful forward-range capability without altering the antenna.

### 3.2.4. System Implications

- Short-/mid-range viability. The measured bandwidth, 16 dBi array gain, and  $\geq 45 \text{ m}$  clear-air reach for car-sized targets exceed SAE Level-2 corner-radar requirements, ensuring reliable blind-spot monitoring, lane-change assistance, and rear cross-traffic alert.
- Hardware headroom. The emitted power of 12 dBm, combined with 16 dBi gain, keeps the effective isotropic radiated power 27 dB below the regulatory 55 dBm limit, leaving ample margin for future beam-forming or MIMO virtual-aperture expansion.

- Weather robustness. Even a worst-case rain cell reduces the sedan-class range by only 4 %, confirming suitability for all-weather ADAS sensing up to  $\sim 50 \text{ m}$ .
- Upgrade path. For highway ACC or imaging-radar duties, the same PCB stack-up could be reused with a wider IF filter ( $\geq 40 \text{ MHz}$ ) and digital sweep compression, extending clear-air detection beyond 200 m while preserving the existing antenna footprint.

### 3.2.5. Limitations and Future Work

The present validation is based on a single reference board, so the statistical impact of process spread—dielectric constant tolerance, copper roughness, and assembly misalignment—remains unknown. A small batch of replicate boards will therefore be fabricated to quantify yield and performance drift. Although full-wave models predict that element-to-element coupling in the  $4 \times 4$  array introduces  $< 0.8 \text{ dB}$  gain ripple and  $< 2^\circ$  beam deflection, these estimates have not yet been confirmed experimentally; a calibrated probe fixture is being designed to measure the full  $16 \times 16$  mutual-coupling matrix at W-band. Thermal behaviour is another practical constraint: worst-case RF dissipation of 0.5 W produces a simulated temperature rise of  $\approx 12 \text{ K}$  in the single-layer PCB. Copper back-plating and a thin aluminium spreader will be added to maintain junction temperatures below  $85^\circ\text{C}$ , and forced-air convection inside the bumper cavity is under evaluation for high-duty-cycle modes.

Contingent on external funding, a four-phase hardware-in-the-loop (HIL) programme is planned. Phase I—laboratory calibration and static characterisation of a TI AWR2944 79 GHz radar SoC coupled to a programmable FMCW target emulator, six-DOF motion table, and CAN-bus interface—will commence within three months of grant award. Phase II will extend over the next six months to execute dynamic bench trials that inject controlled radial and angular motions. Phase III will transfer the system to an instrumented vehicle during the following academic semester to evaluate real-time ranging and classification in live traffic. Phase IV will conduct a year-long durability campaign with iterative firmware optimisation to track ageing and drift. Results from each phase will be disseminated in subsequent publications.

Current validation relied on a single prototype board; additional samples will be fabricated to assess process spread. Mutual coupling within the  $4 \times 4$  array has been accounted for in simulation but not yet

verified experimentally. Contingent on external funding, a four-phase hardware-in-the-loop (HIL) programme is also envisaged: Phase I—laboratory calibration and static characterization of a TI AWR2944 79 GHz radar SoC integrated with a programmable FMCW target emulator, six-DOF motion table, and CAN-bus interface—will begin within three months of grant approval; Phase II—dynamic bench trials—will follow over the subsequent six months; Phase III—on-vehicle road tests for real-time ranging and classification—will start in the next academic semester; and Phase IV—year-long durability monitoring with iterative firmware optimization—will finalize the campaign, with findings to be reported in future work.

#### 4. CONCLUSION

This work demonstrates that a single-layer RO3003 front-end can satisfy the electrical and link-budget demands of W-band automotive radar. The main performance metrics are:

- Broadside gain: 16 dBi (4 × 4 array)
- Impedance bandwidth: 3.2 GHz (−10 dB, 76–81 GHz fully covered)
- Detection range (sedan RCS = 100 m<sup>2</sup>): 51 m clear air, 49 m heavy rain ( $\gamma = 8$  dB km<sup>−1</sup>)
- Range / velocity resolution: 3.75 cm, 0.89 km h<sup>−1</sup> (4 GHz sweep, 60  $\mu$ s chirp, 128-chirp frame)

These figures confirm centimetre-class resolution, robust mid-range coverage, and all-weather resilience while remaining 27 dB below the 55 dBm EIRP ceiling. Consequently, the proposed architecture fulfils SAE Level-2 ADAS requirements for blind-spot warning, lane-change assist, and autonomous emergency braking. Moreover, its wide bandwidth and scalable array layout provide a viable springboard toward next-generation imaging radars for high-definition mapping, automated valet parking, and adaptive cruise control in complex urban scenes.

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#### CONFLICTS OF INTEREST

The author declared no conflicts of interest.

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