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A V-band high-linearity BiCMOS mixer with robust temperature tolerance

Key words: V-band; Down-conversion mixer; SiGe BiCMOS; Temperature compensation; High-linearity; Active balun

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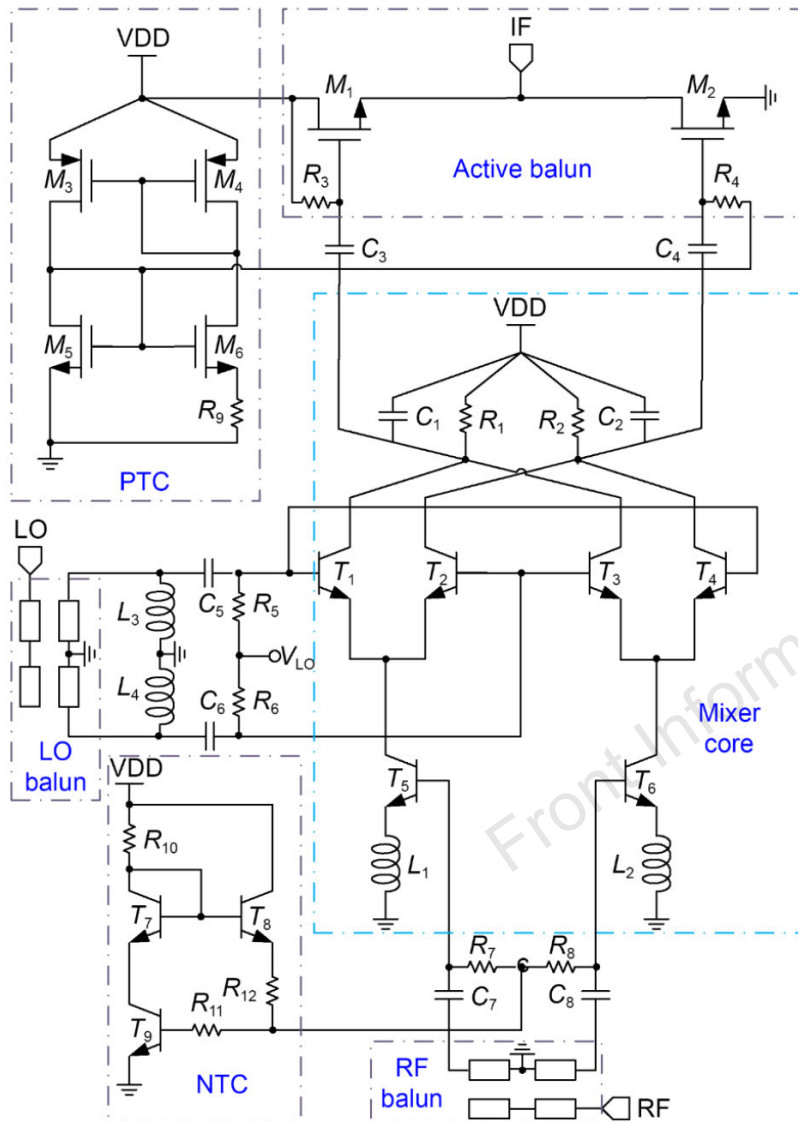
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Motivation

- As a critical foundational component of receivers, down-conversion mixers transform radio frequency signals into intermediate frequency or baseband signals.
- However, the behavior of silicon-based mixers, including metrics like conversion gain (CG), noise figure (NF), and linearity, can exhibit significant fluctuations with varying ambient temperatures, thereby directly causing deterioration of receiver sensitivity and dynamic range.
- Therefore, it is highly anticipated that the mixers exhibit excellent robustness against temperature variation.

Main idea

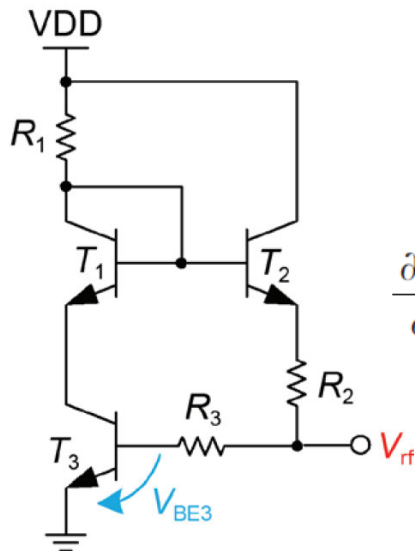


Schematic of the proposed V-band mixer

- The mixer's temperature robustness has been greatly enhanced by employing a negative temperature-compensation circuit (NTC) and a positive temperature-compensation circuit (PTC) in the transconductance (g_m) stage and intermediate frequency (IF) output buffer, respectively.
- Benefiting from the active balun with enhanced g_m and emitter negative feedback technique, the linearity of the mixer has been significantly improved.

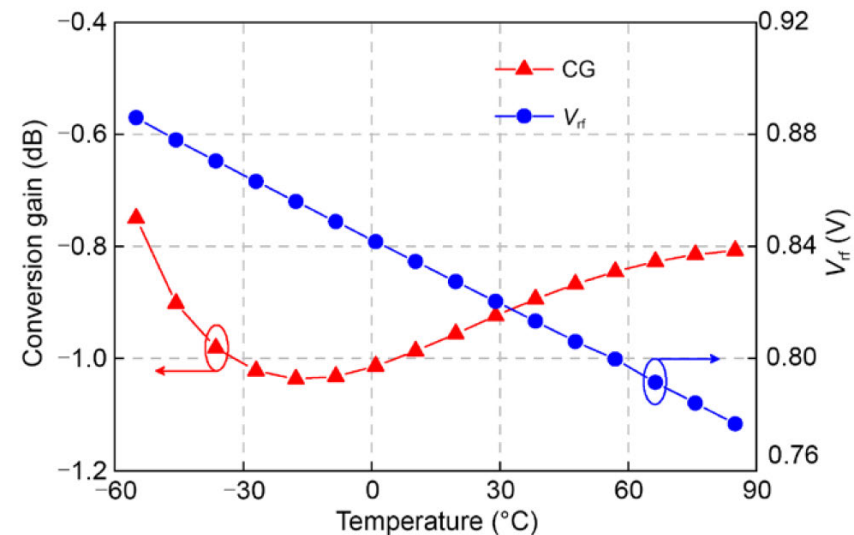
NTC design

- The collector current of the g_m stage transistors increases significantly with ambient temperature.
- CG is directly associated with the collector current.
- Thus, temperature compensation for CG can be achieved by generating a negative temperature coefficient base current to reduce the fluctuation of the collector current.



$$\frac{\partial V_{rf}}{\partial T} = \frac{V_{BE3} - (4 + m)V_T - \frac{E_g}{q}}{T}$$

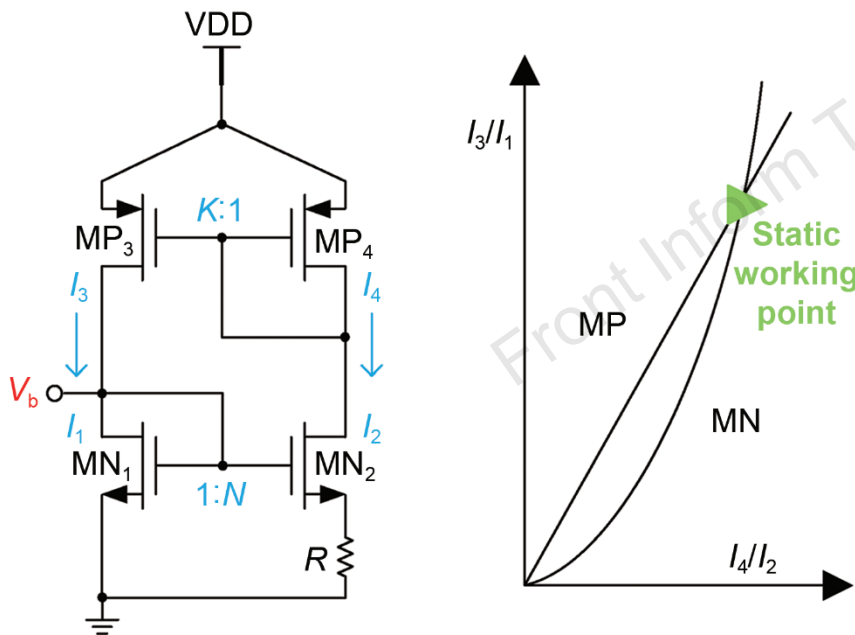
The proposed NTC



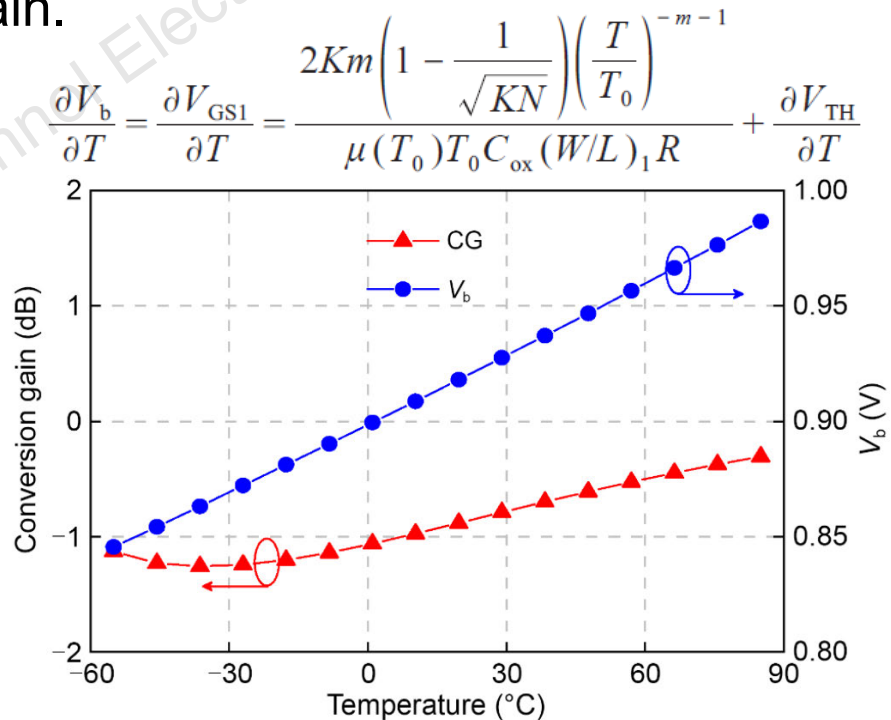
Simulated results of temperature variation vs. CG and output voltage V_{rf}

PTC design

- Due to intrinsic factors within the NMOSFET device, g_m of the NMOSFET devices decreases with increasing temperature, thereby reducing the gain of the output IF buffer.
- By increasing the bias voltage of the NMOSFET transistors, g_m can be enhanced to compensate for the gain.



PTC and its static working point

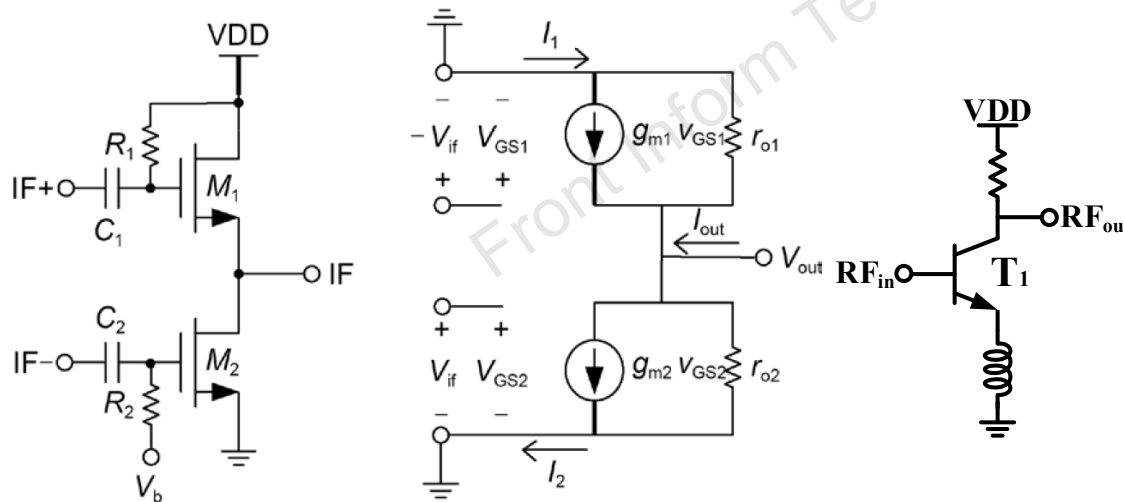


Simulated results of temperature vs. CG and bias voltage.

Linearized design

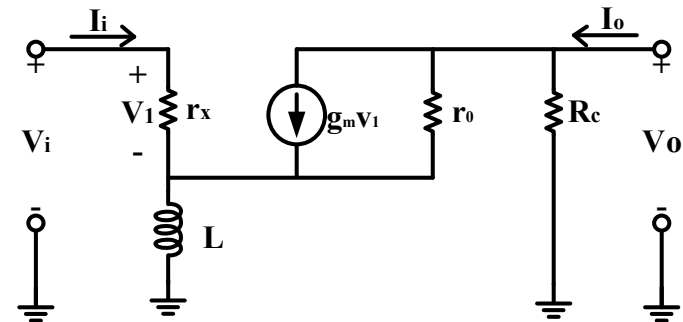
- The active balun serves as an output IF buffer while converting from differential to single-ended signals, achieving impedance matching and high linearity simultaneously.
- Introducing a negative feedback inductor suppresses the transconductance nonlinearity and thus improves the linearity of the mixer.

$$I_{out} = I_1 - I_2 = -V_{if} \left(g_{m1} + g_{m2} + \frac{1}{r_{o1}} + \frac{2}{r_{o2}} \right)$$



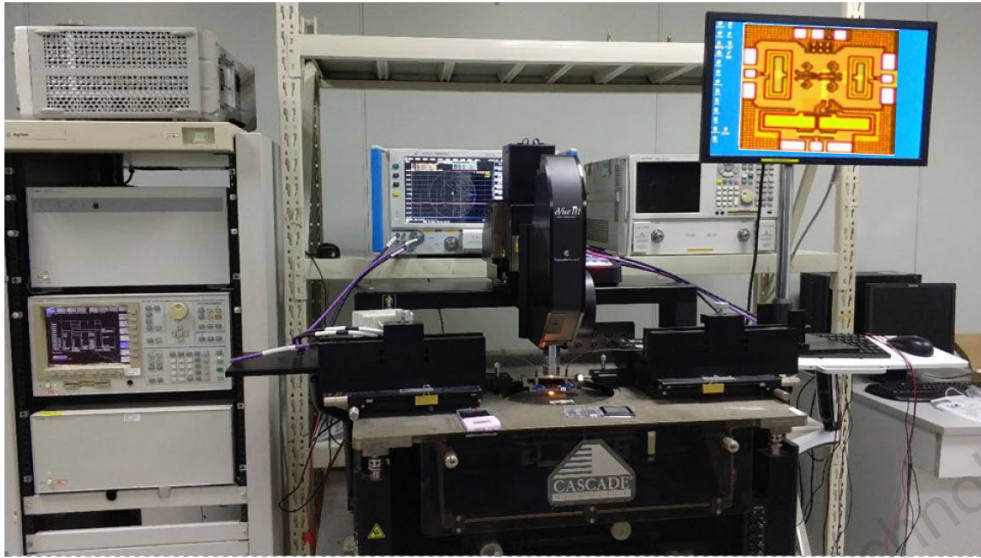
Schematic of active balun and its small signal equivalent model

$$\frac{V_o}{V_i} = \frac{-g_m R_c}{1 + j\omega L g_m - g_m R_c}$$



Schematic of g_m stage and its small signal equivalent model

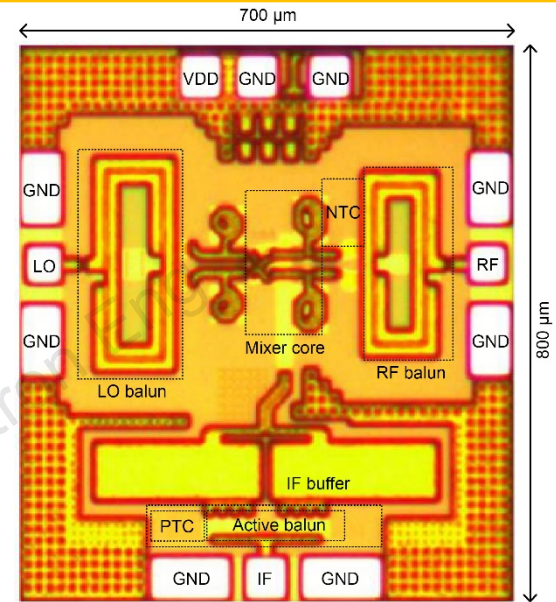
Test platform



Photograph of test platform

◆ Test equipment:

- ✓ Probe table TS200-SE
- ✓ GSG probe ASP40-A-GSG-150
- ✓ Vector Network Analyzer keysight PNA-X-N5247B
- ✓ DC Analyzer Keysight N6705C
- ✓ Temperature control system: ERS AC3 Fusion thermal chuck system
- ✓ Straightener N9398F

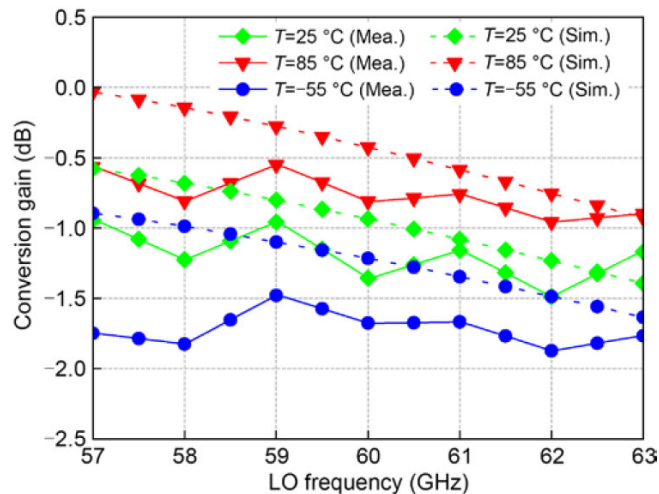


Micrograph of V-band mixer chip

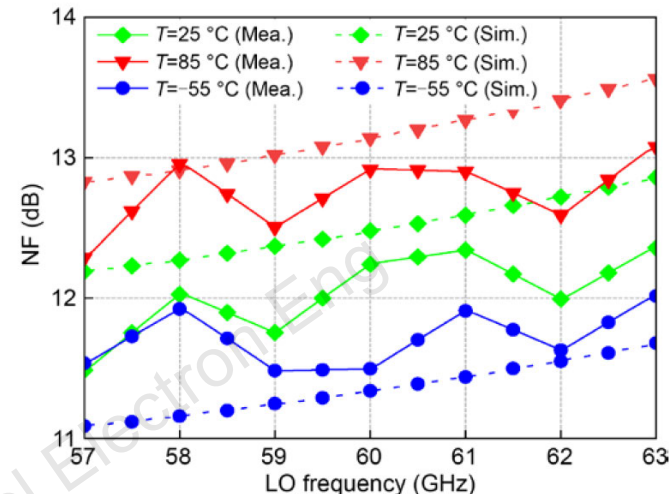
◆ Test condition:

- ✓ Working Voltage: $V_{DD}=2.5\text{ V}$
- ✓ P_{LO} : -3 dBm
- ✓ P_{RF} : -20 dBm
- ✓ F_{RF} : $57\sim63\text{ GHz}$
- ✓ F_{LO} : $57\sim63\text{ GHz}$
- ✓ F_{IF} : 100 MHz

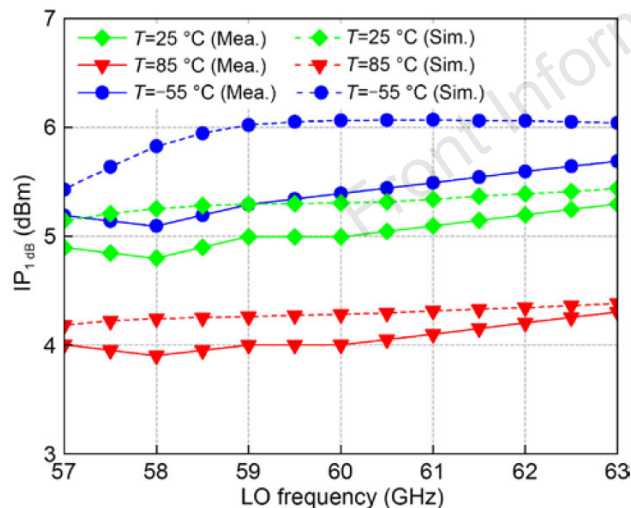
Test results



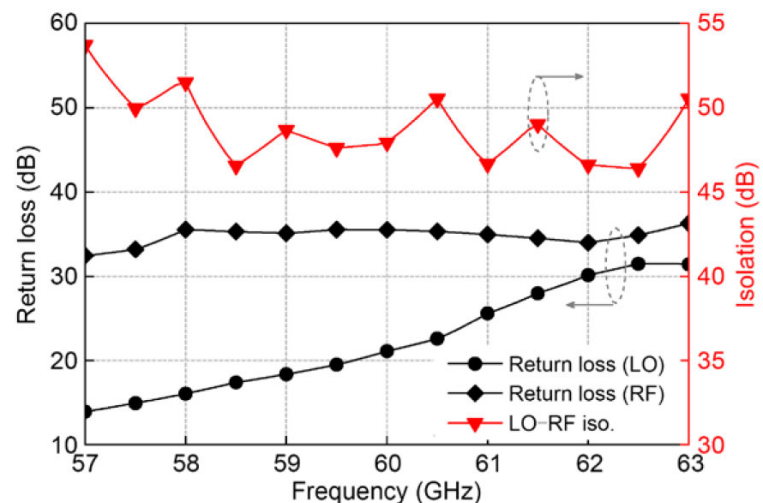
Measured and simulated CG under -55 °C, 25 °C, and 85 °C, respectively



Measured and simulated NF under -55 °C, 25 °C, and 85 °C, respectively



Measured and simulated IP_{1dB} under -55 °C, 25 °C, and 85 °C, respectively



Measured return loss and isolation

Performance Summary and Comparison

Reference	Temperature (°C)	Process	Frequency (GHz)	P_{LO} (dBm)	CG (dB)	NF (dB)	$IP_{1\text{ dB}}$ (dBm)	LO–RF iso. (dB)	Power (mW)	Area (mm ²)
Mazor et al., 2017	−55~85	130 nm SiGe	57~66	0	6.1~8.8*	11.4~13.3*	−9.5~−3.4*	>46*	55^	0.47
Yu et al., 2024	−20~100	28 nm CMOS	60~90	N/A	16~18.4	7.5~11.2	−5~−4	>35.8	41.5^	0.46
Ciocoveanu et al., 2018	−30~120	28 nm CMOS	60	−2	2.9~6.5#	11~13.7#	−4.2~−1.8#	N/A	1.8^	0.24
Duan et al., 2023	−45~125	65 nm CMOS	76~83	N/A	26~68\$	11.2~12.5	−7	N/A	N/A	0.85
This work	−55~85	130 nm SiGe	57~63	−3	−1.6~−0.8	11.5~12.5	4~5.2	>46	15.7~21	0.56

Post-layout simulation results, * chart estimation, ^ at room temperature, \$ with low noise figure amplifier, N/A: no data

Conclusions

- A positive and negative temperature-compensation technique is developed and successfully implemented in a V-band down-conversion mixer using a 130 nm SiGe BiCMOS process.
- In the temperature span from $-55\text{ }^{\circ}\text{C}$ to $85\text{ }^{\circ}\text{C}$, the variations in CG, NF, and $IP_{1\text{ dB}}$ measurements are all superior to 0.8 dB, 1 dB, and 1.2 dBm, respectively.
- The incorporation of emitter negative feedback and an active balun has greatly improved the mixer's linearity. Consequently, within the frequency range of 57–63 GHz, the measured $IP_{1\text{ dB}}$ exceeds 5.1 dBm, 4.8 dBm, and 3.9 dBm at temperatures of $-55\text{ }^{\circ}\text{C}$, $25\text{ }^{\circ}\text{C}$, and $85\text{ }^{\circ}\text{C}$, respectively. Furthermore, at temperatures of $-55\text{ }^{\circ}\text{C}$, $25\text{ }^{\circ}\text{C}$, and $85\text{ }^{\circ}\text{C}$, the mixer consumes DC power of 15.75 mW, 18.5 mW, and 21 mW, respectively.



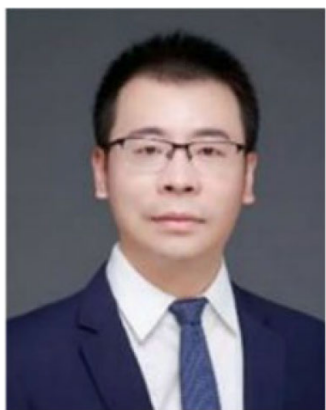
Jiang Luo received the Ph.D. degree in microelectronics and solid-state electronics from Wuhan University, Wuhan, China, in 2018. From 2018 to 2021, he was with Nanjing Electronic Devices Institute, Nanjing, China, as the Senior Research Engineer in RF/mm-wave integrated circuit/system design. He joined Hangzhou Dianzi University, Hangzhou, China, in 2021, where he is currently an Associate Professor with the School of Electronics and Information. He is also currently with the State Key Laboratory of Millimeter Waves, Southeast University, Nanjing, as a Visiting Researcher. His current research interests include analog/RF/mm-wave/terahertz integrated circuit and system design in CMOS/ SiGe BiCMOS for wireless communication and radar applications.



Yizhao Li was born in Ningde, Fujian, China, in 1994. He is currently pursuing the master's degree with School of Electronics and Information Engineering, Hangzhou Dianzi University. His research focuses on the design of silicon-based millimeter-wave frequency conversion circuits.



Yao Peng received the M.S. from the School of Physics and Technology, Wuhan University, China, in 2019. His research interest includes RF/mm-wave integrated circuits and systems for wireless applications.



Qiang Cheng received the B.S. and M.S. degrees from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2001 and 2004, respectively, and the Ph.D. degree from Southeast University, Nanjing, in 2008. In 2008, he joined the State Key Laboratory of Millimeter Waves at Southeast University, where he is the Chief Professor and the Deputy Director of the State Key Laboratory of Millimeter Waves. He is the winner of the National Natural Science Foundation Outstanding Youth Fund, the Young Scholar of Changjiang Scholars Award Program, and the first batch of Outstanding Youth Fund in Jiangsu Province. He is supported by the New Century Outstanding Talents Support Program of the Ministry of Education, Jiangsu Province 333 Talent Project, Jiangsu Province Six Talent Peak Program, and engaged in electromagnetic metamaterial research for a long time, selected as a citation scholar of Cerebral Safety. Dr. Cheng's research work was selected as the Second Prize of the National Natural Science Award in 2014 and 2018, the First Prize of the Natural Science Award of the Ministry of Education in 2011, and the Top Ten Scientific and Technological Progress of Chinese Universities in 2021.