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Analysis and design of transformer-based CMOS ultra-wideband millimeter-wave circuits for wireless applications: a review

Key words: CMOS; Millimeter-wave (mm-Wave); Ultra-wideband; Transformer; Low-noise amplifier; Injection-locked frequency tripler; Injection-locked frequency divider; Mixer

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Motivation

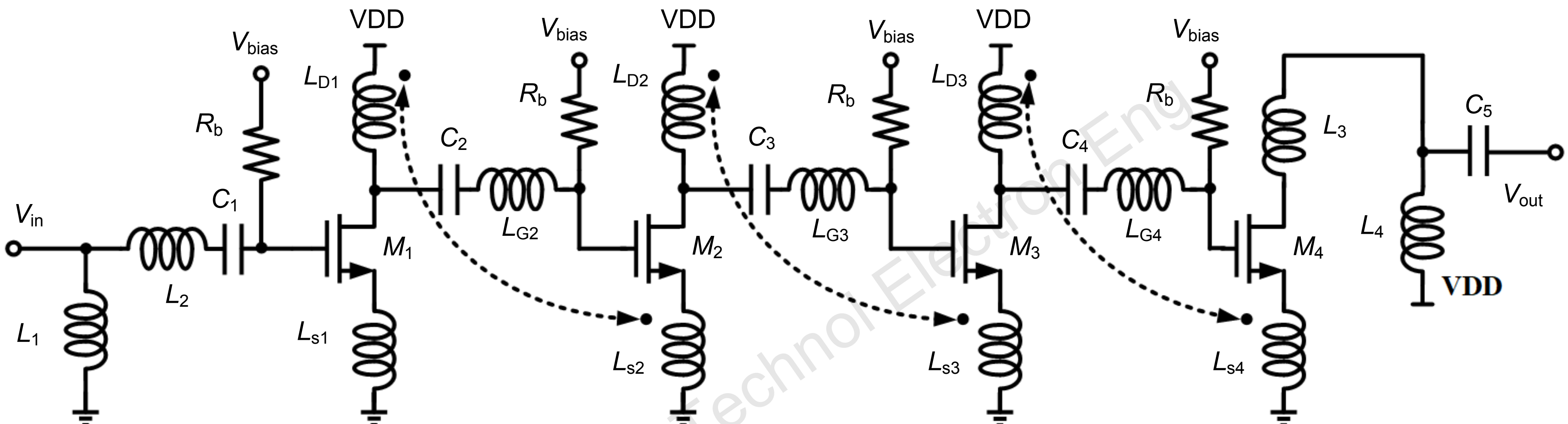
- Millimeter-wave (mm-Wave) wideband circuits and systems, which can cover two or more frequency bands, can greatly reduce the number and the cost of wireless devices.
- CMOS technologies have notable advantages of low cost, high reliability, and high integration, while they encounter several serious technical challenges to meet the requirement of commercial application, e.g., high noise figure (NF), low gain, low output power, and narrow operating bandwidth.

Main idea

On-chip transformer-based techniques and high-order networks are used to extend the bandwidth of CMOS mm-Wave circuits:

- ■ Transformer-based Gm-boosting and pole-tuning technique for low noise amplifiers
- ■ Injection-current-boosting technique and transformer-based high-order resonators for injection-locked frequency multipliers and dividers
- ■ Two-path transconductance stage and transformer-based loads for up-conversion mixers

1. Ultra-wideband mm-Wave LNA

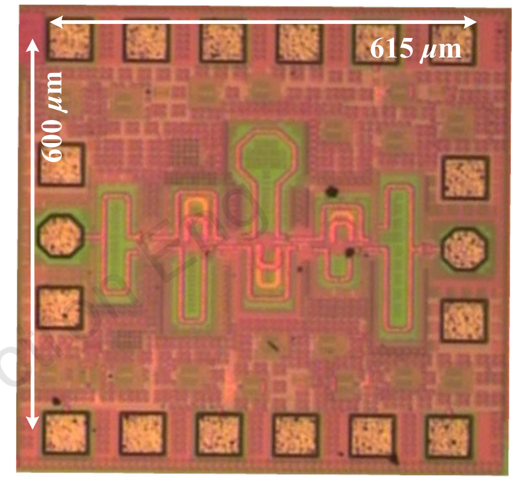


Schematic of the mm-Wave LNA

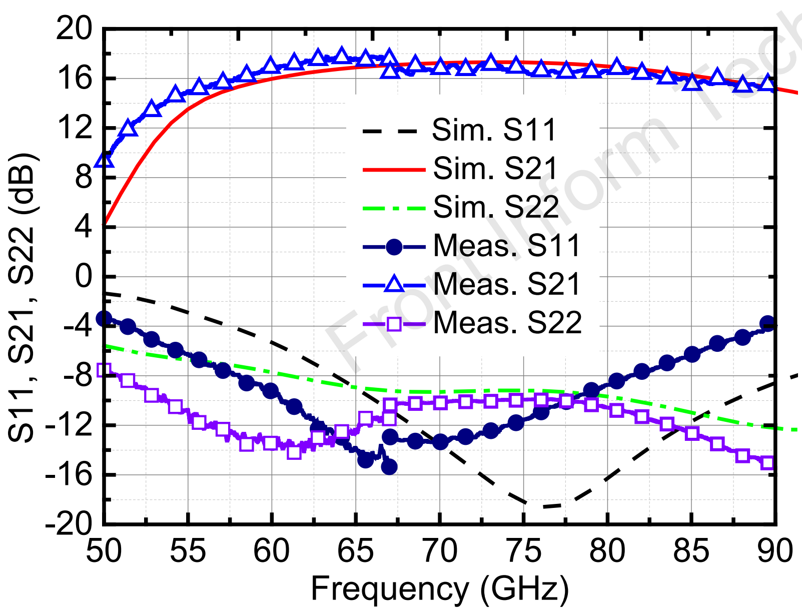
- ✓ The novel transformer-based Gm-boosting technique is applied to obtain comparable power gain and NF.
- ✓A pole-tuning technique realized by gate-series inductors is used to adjust the main pole of the inter-stage matching networks and extend bandwidth.

1. Ultra-wideband mm-Wave LNA

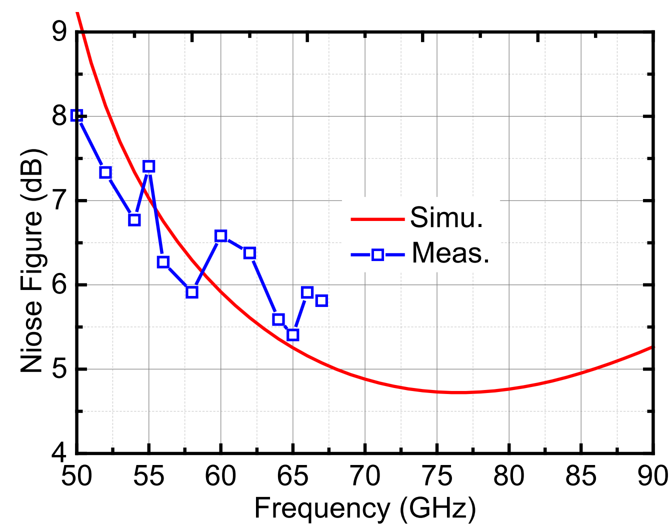
- ✓ Frequency: 54.4–90 GHz
- ✓ Maximum gain: 17.7 dB
- ✓ Noise figure: 5.4–7.4 dB (tested)
- ✓ Chip area: 0.37 mm^2



Chip photo of the mm-Wave LNA

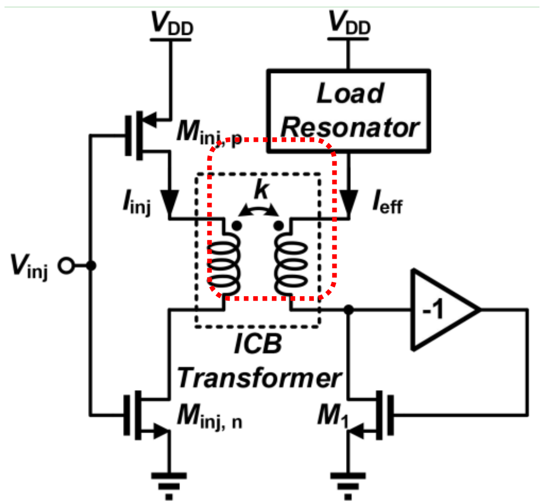


S parameters of the mm-Wave LNA

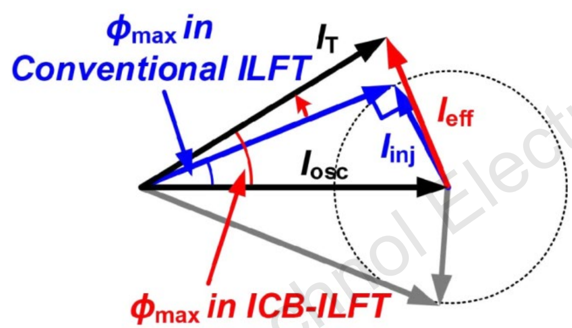


Noise figure of the mm-Wave LNA

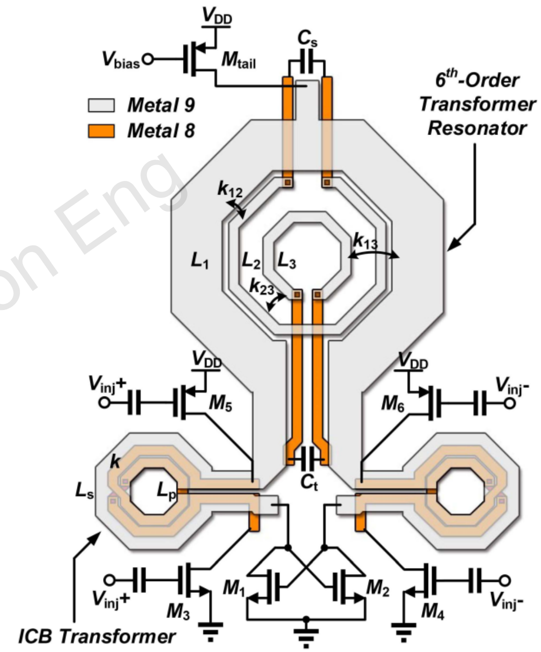
2. Ultra-wideband mm-Wave injection-locked frequency tripler (ILFT)



Simplified model



Phasor diagram

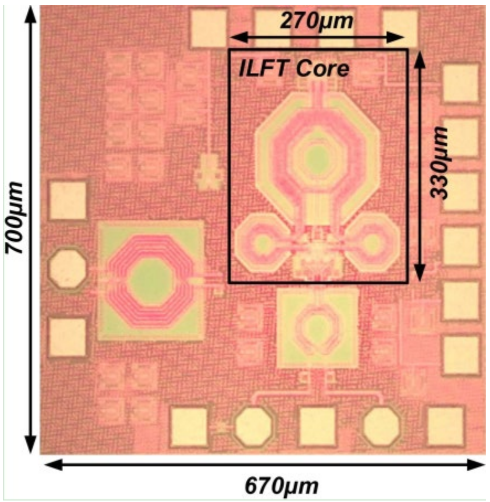


Schematic

✓An injection-current-boosting technique is introduced to increase the locking range of ILFT.

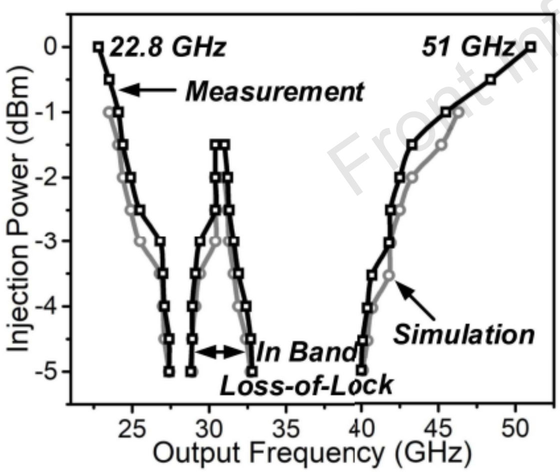
✓The transformer is used to realize the six-order injection-coupling network.

2. Ultra-wideband mm-Wave injection-locked frequency tripler (ILFT)

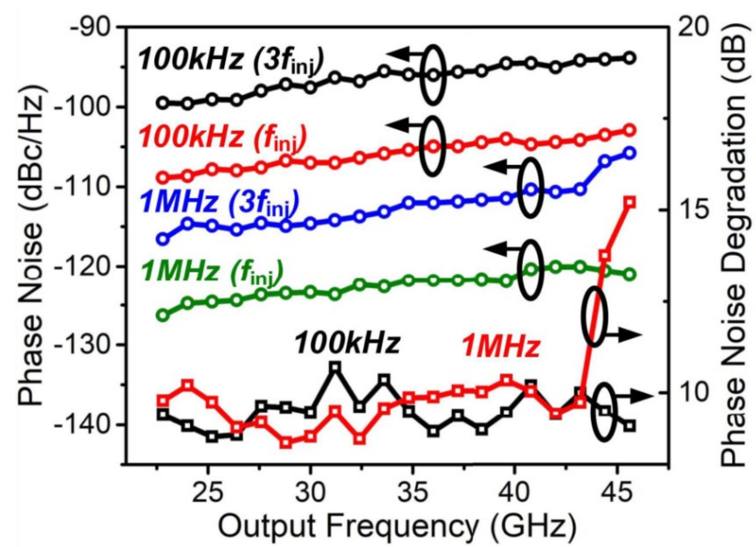


Chip photo of the mm-Wave ILFT

- ✓ Frequency: 22.8–43.2 GHz
- ✓ Supply voltage: 1.2 V
- ✓ Locking range: 28.2 GHz (76.4%)
- ✓ DC power: 14.8 mW
- ✓ Chip area: 0.09 mm^2

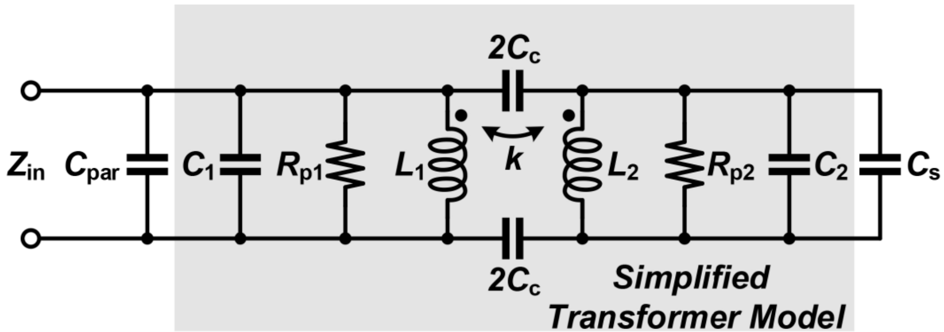


Locking range of the mm-Wave ILFT

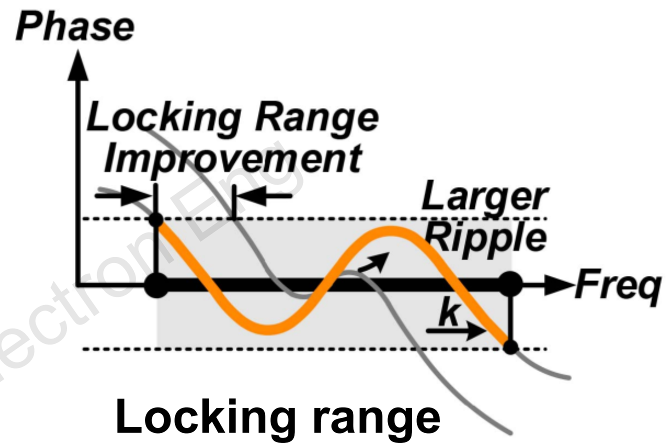


Phase noise of the mm-Wave ILFT

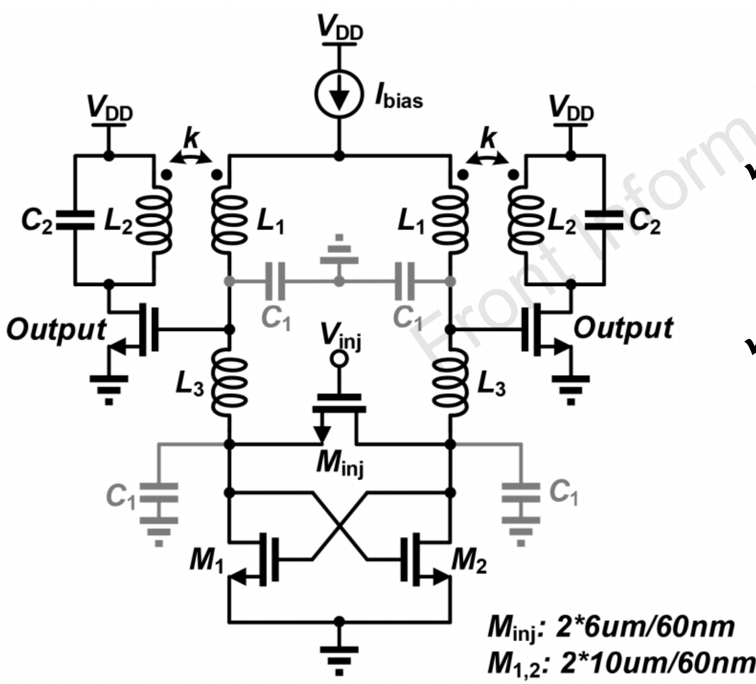
3. Ultra-wideband mm-Wave injection-locked frequency divider (ILFD)



Resonator model



Locking range

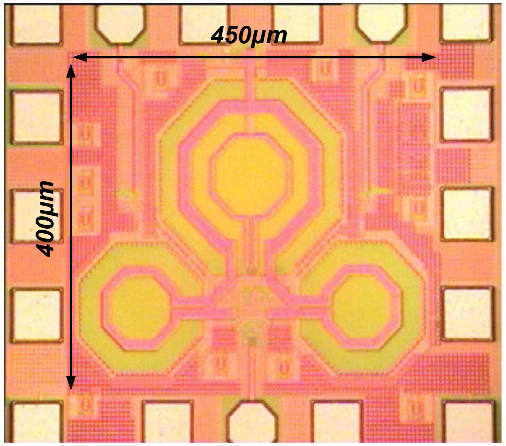


Schematic

✓Transformer-based high-order resonators are used to achieve a wide locking range.

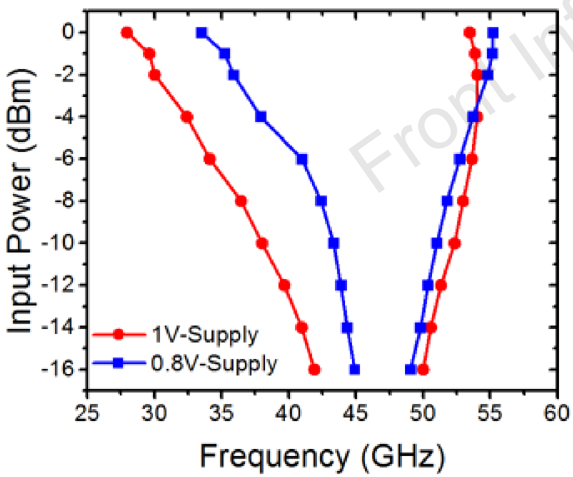
✓Two gain-peaking inductors are applied to strengthen the condition of oscillation and reduce the DC power consumption.

3. Ultra-wideband mm-Wave injection-locked frequency tripler (ILFD)

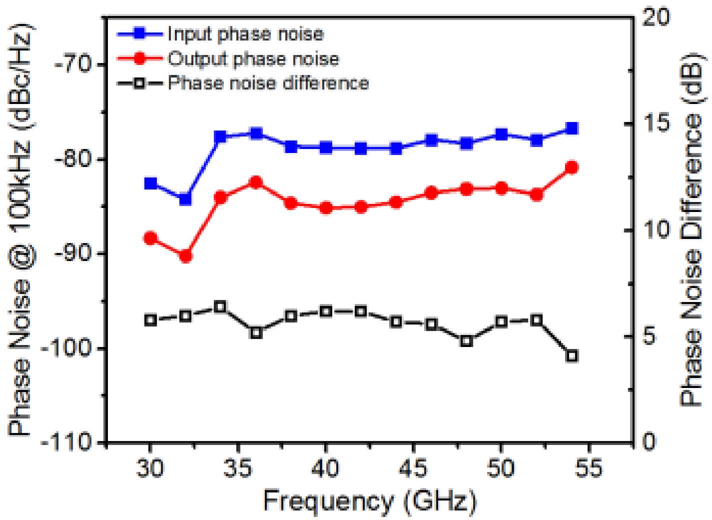


Chip photo of the mm-Wave ILFD

- ✓ Frequency: 27.9–53.5 GHz
- ✓ Supply voltage: 0.6–1.2 V
- ✓ Locking range: 25.6 GHz (62.9%)
- ✓ DC power: 5.8 mW
- ✓ Chip area: 0.18 mm^2

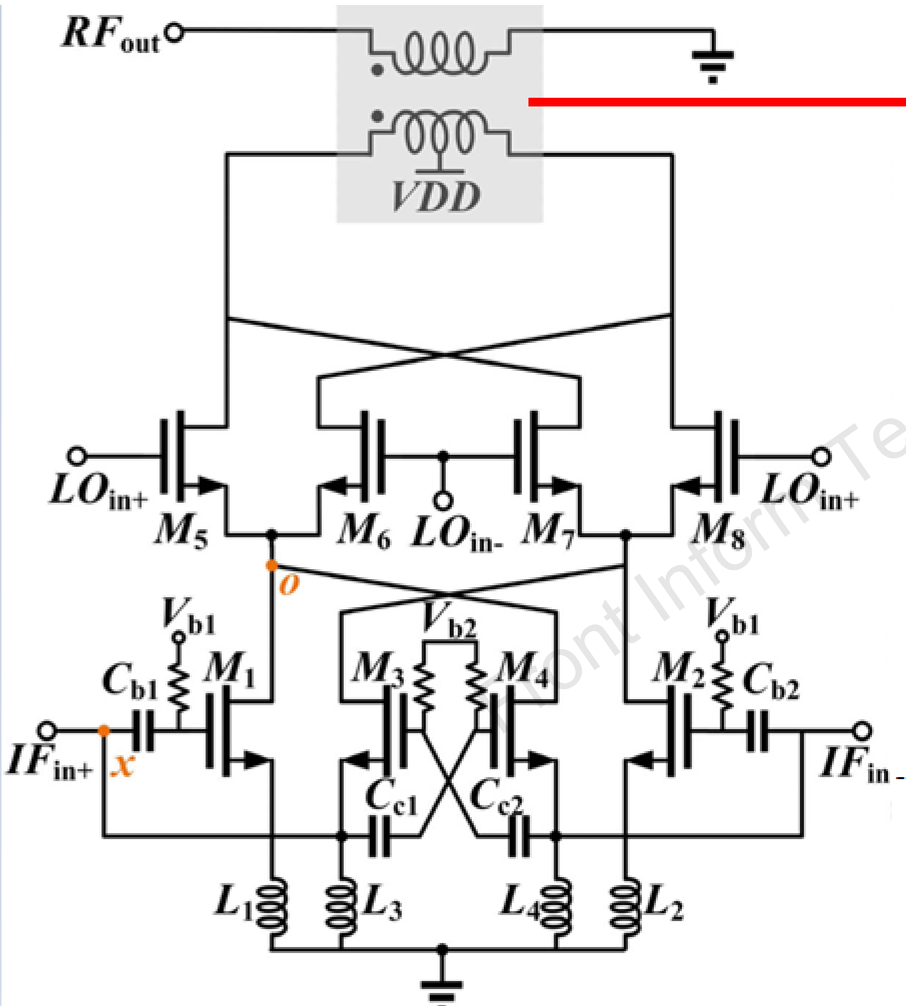


Locking range of the mm-Wave ILFD

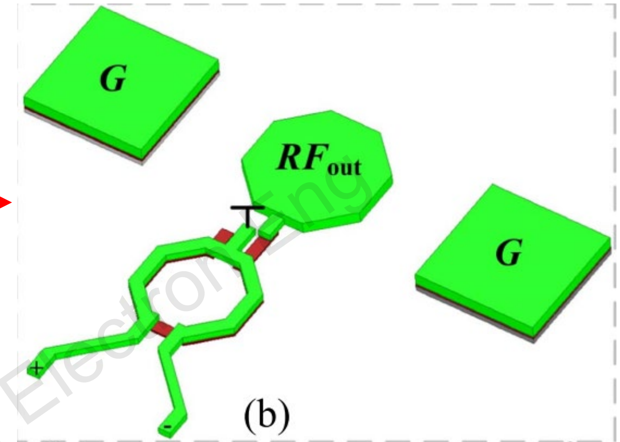


Phase noise of the mm-Wave ILFD

4. Ultra-wideband high-linearity mm-Wave up-conversion mixer



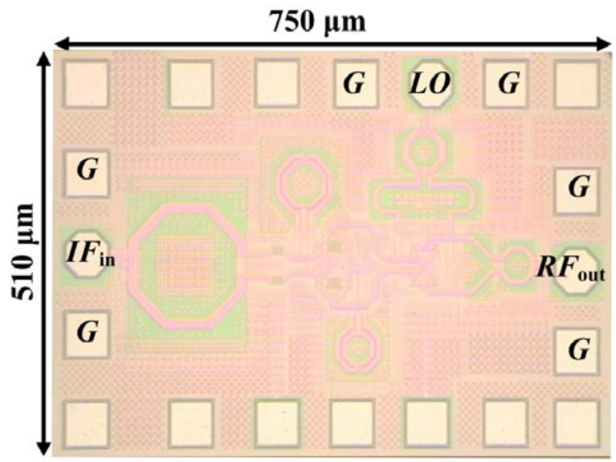
Schematic of the mixer



Output matching network

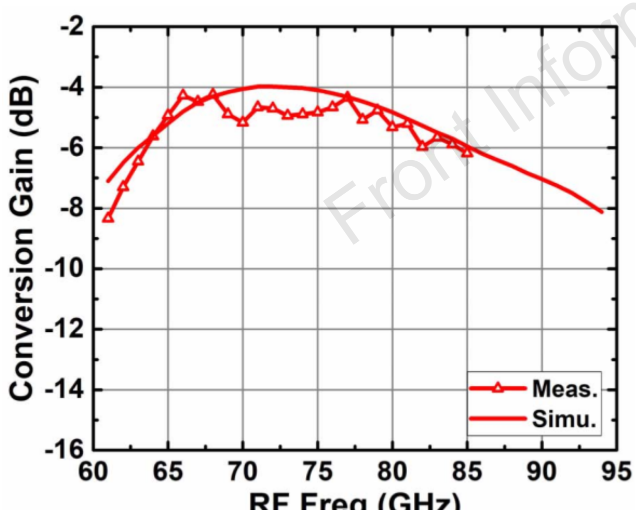
- ✓A two-path transconductance stage is used to suppress the high-order distortion and reduce the impedance variation with frequency.
- ✓High-order load realized by a transformer is used as an output impedance matching network to improve the RF bandwidth.

4. Ultra-wideband high-linearity mm-Wave up-conversion mixer

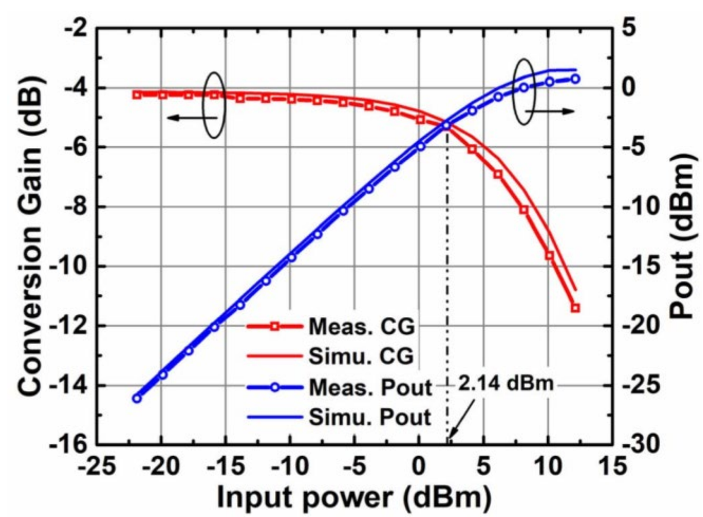


Chip photo of the mm-Wave mixer

- ✓ RF frequency: 62–85 GHz
- ✓ IF bandwidth: 18 GHz
- ✓ Conversion gain: –4.3 dB
- ✓ Input $P_{1\ \mathrm{dB}}$: 2.14 dBm
- ✓ DC power: 10.8 mW
- ✓ Chip area: 0.38 mm^2



Conversion gain of the mixer



Linearity of the mixer

Conclusions

- For mm-Wave amplifiers, the transformer-based Gm-boosting technique is beneficial to noise and gain performance, and the pole-tuning method can extend the gain bandwidth.
- The transformer-based high-order resonator is a useful way to enhance the operating bandwidth of ILFDs and ILFMs.
- A two-path transconductance stage and transformer-based load are helpful in improving the linearity and bandwidth of the mm-Wave mixer.