A 190-210GHz Power Amplifier with 17.7-18.5dBm Output Power and 6.9-8.5% PAE

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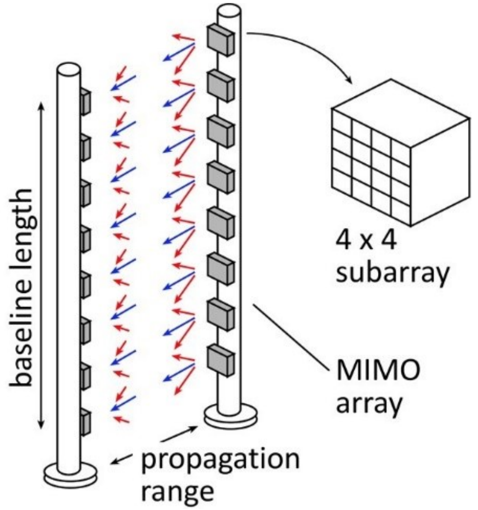
Outline

- Motivation for mm-wave frequencies and prior work.
- Application for the amplifier.
- Amplifier design
  - Power and driver cells
  - Low-loss compact combiner
- Measurement results
- Summary and conclusion

mm-wave Communication (140-1000 GHz)

- Objective
  - –Support high data rate communication.
  - –Spatial multiplexing for high capacity.
  - –Cover long distance.
- Benefits (140- 1000 GHz)
  - –Large available spectrum, high data rate.
  - –Shorter λ: more channels for the same array size.
- Challenge
  - –Atmospheric attenuation is high $P_R \alpha \frac{\lambda^2}{R^2} e^{-\alpha R}$.



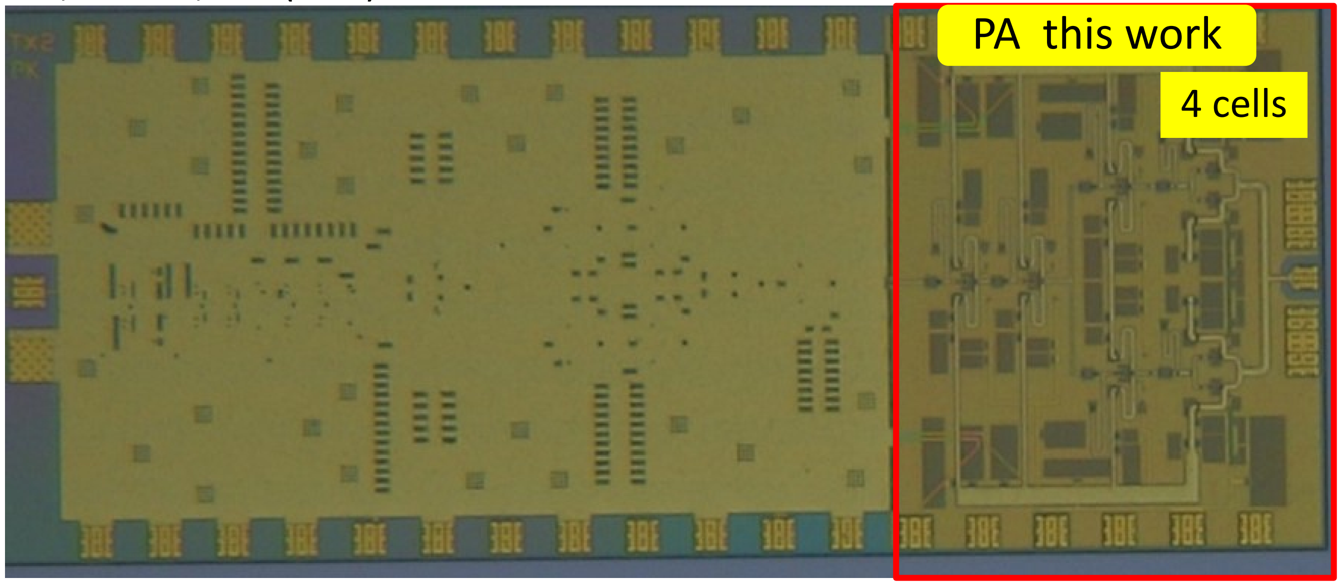
Prior Work at G-band

- At 200GHz, CMOS shows 9.4dBm with only 1.03% PAE [2].
- SiGe shows 13.5dBm with ~2% drain efficiency [3]
- GaN demonstrates higher power with <2.4% peak PAE [4], [5].
- InP presented the highest power and efficiency [6]-[18].
- Key points
  - Designs are not optimized for the highest PAE at OP_{1dB}. PAE at OP_{1dB}<3%
  - Power measurement accuracy at the linear region is challenging.

This Work (190-210GHz)

- Optimize for the highest efficiency at OP_{1dB}.
- OP_{1dB}~17.4dBm, PAE: 6.4% at OP_{1dB}, Gain~23dB.
- Accurate power measurement at the linear region.
- This amplifier is integrated to a 200GHz transmitter (not published).

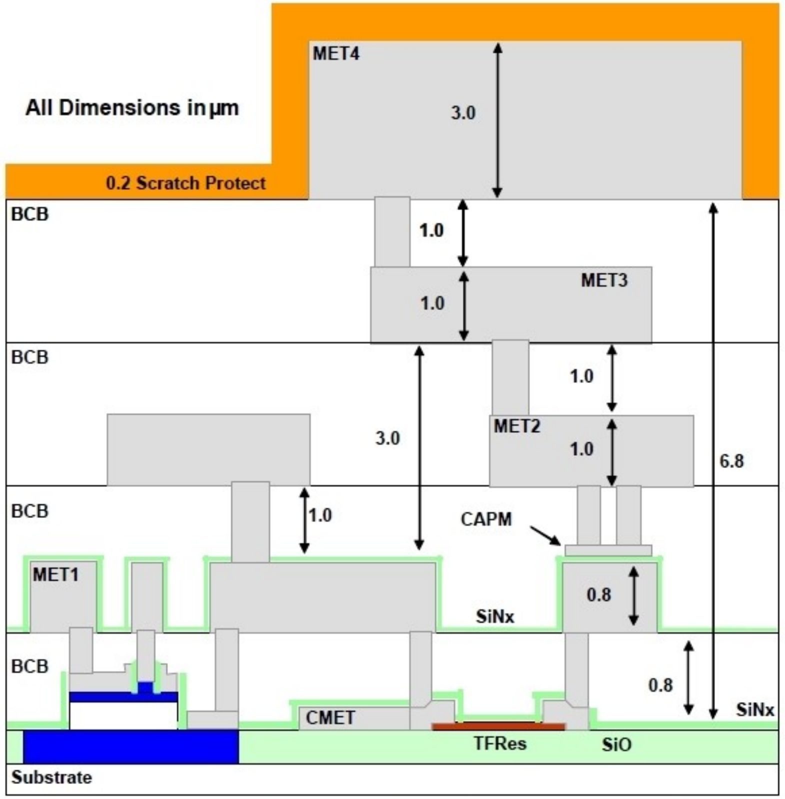
2,900 x 1,200 (um^2)



200GHz transmitter, not published

250nm InP HBT Process (Teledyne [6])

- Mm-wave amplifier requires fast technologies.
- f_{max}=650GHz.
- BV_{CEo}=4.5V.
- J_{max}=3mA/µm.
- Four Au interconnect.
- MIM cap (0.3fF/µm2).
- TFR (50Ω/square).

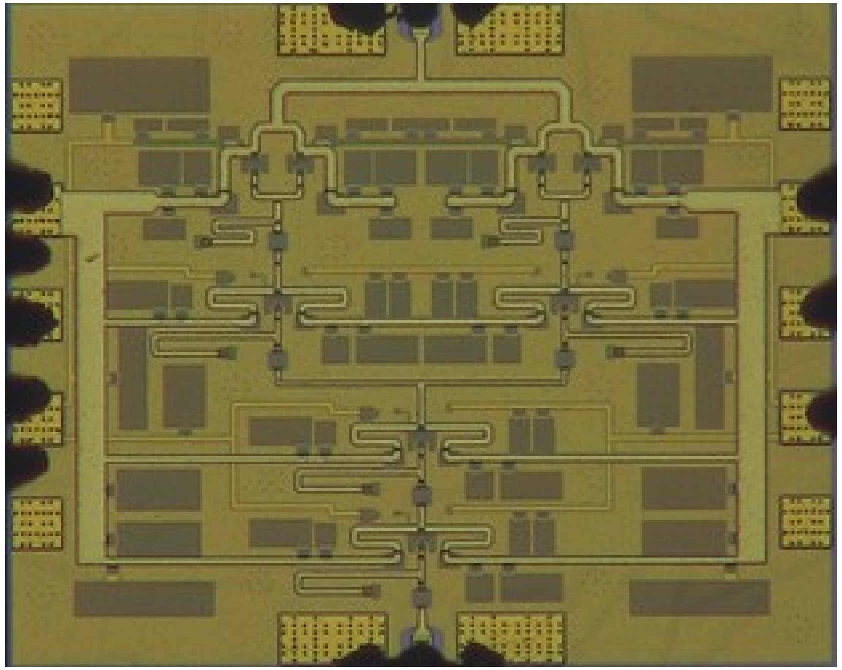


Cross section of TSC250 IC

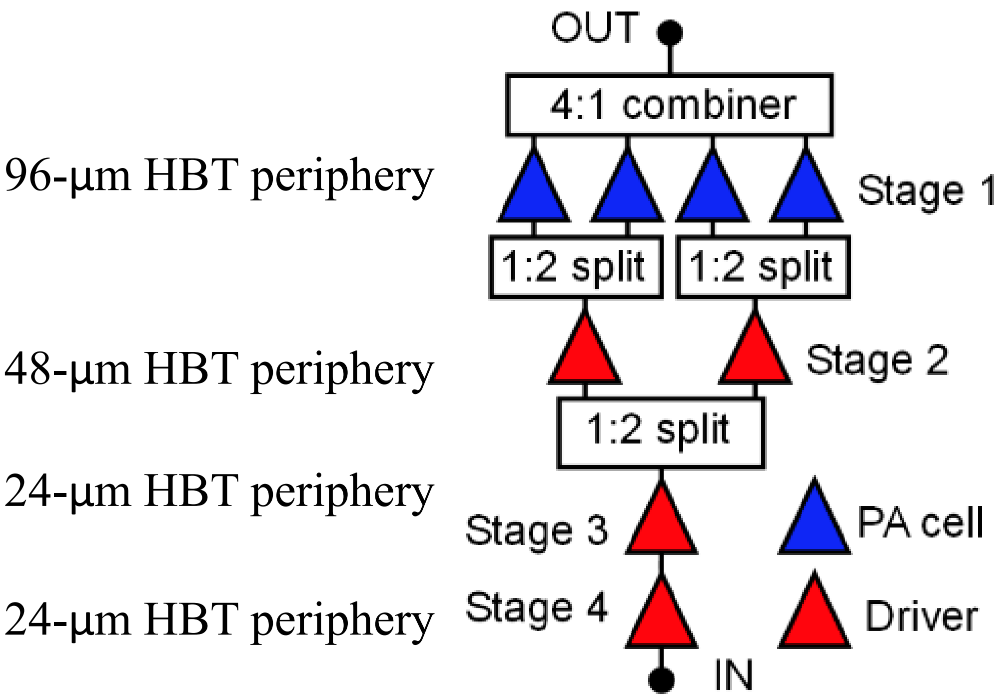
Power Amplifier Design

- Four stages amplifier.
- Combine four power cells.
- Driver scaling sustains good PAE.

- Power combining techniques
  - Parallel combining: 4:1 transmission line combiner.
  - Series combiner: stacked unit cell.



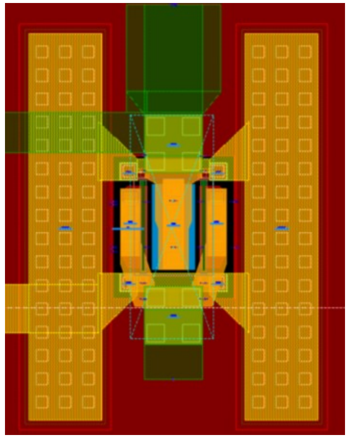
Amplifier micrograph



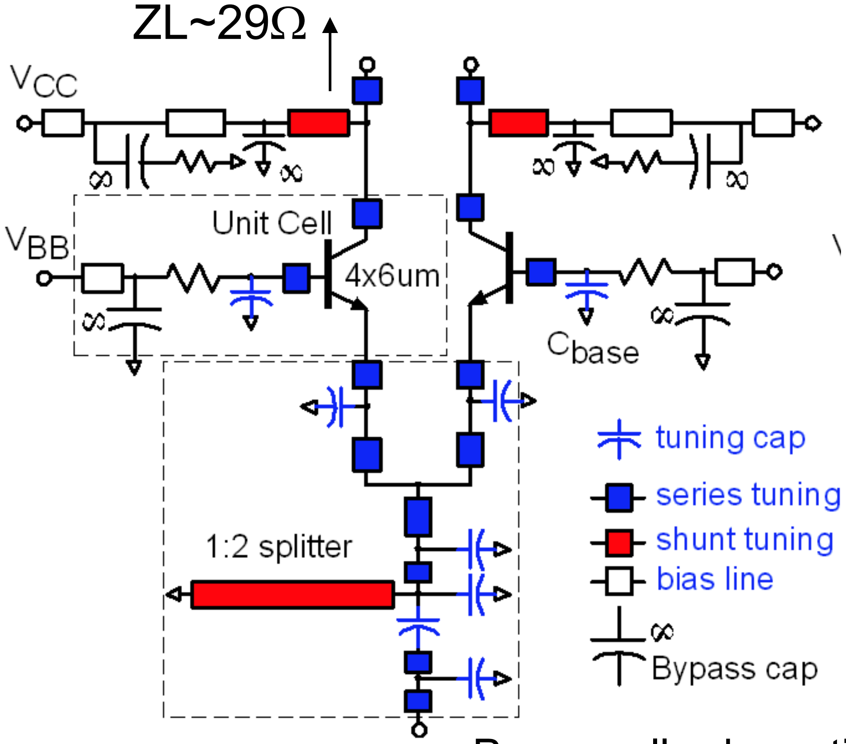
Amplifier block diagram

Power Cell Design

- CB architecture with finite base impedance.
  - Superior PAE at OP_{1dB}, compared to CE or grounded CB, due to the feedback linearization [14].
- Base capacitances
  - Maximum value: limited by the self resonance frequency.
  - Minimum value: limited by the acceptable gain.
- Shunt transmission lines tunes the transistor parasitics.
- Each cell requires ~29Ω load impedance.
- Matching considerations
  - Staggered tuning for better bandwidth.
  - Input impedances are close to the loadline of the driver to ensure proper saturation.



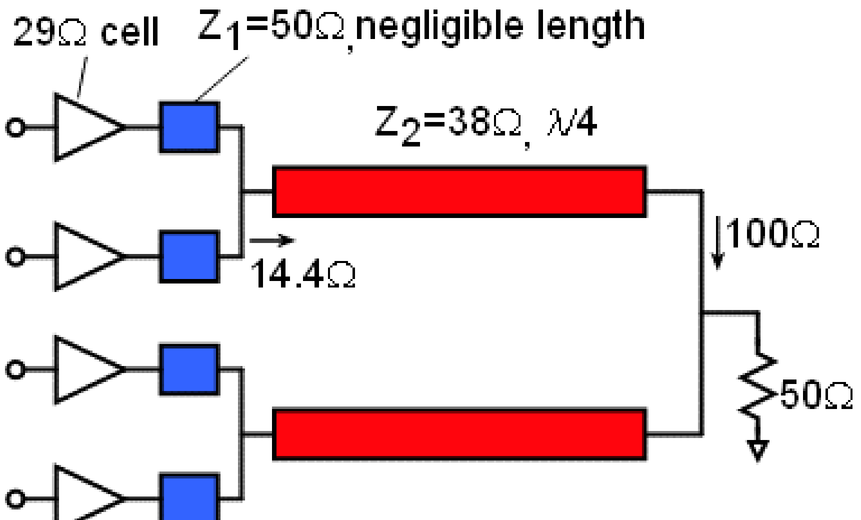
Transistor footprint with cap



Power cell schematic

Combiner Design

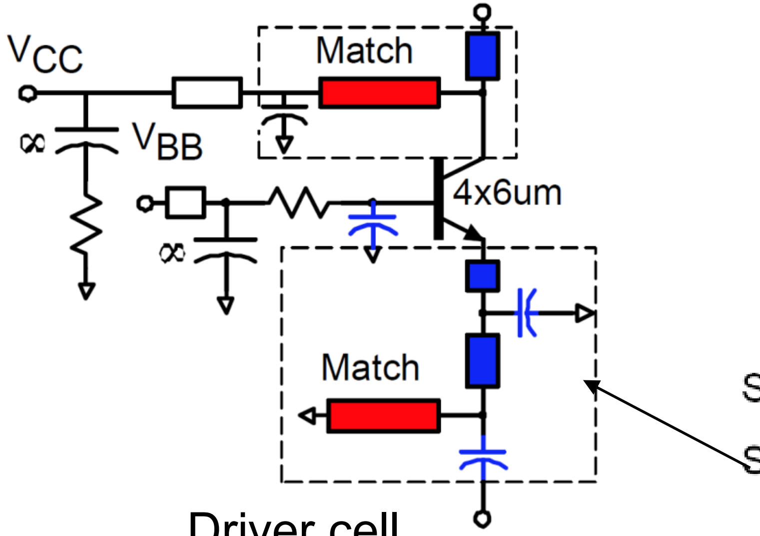
- Transmission line combiners have low loss and very compact [14], [15], [17].
- Low loss 4:1 transmission line combiner.
- Combiner transforms 50Ω to the required loadline impedance for each cell (~29Ω) using a single $\lambda/4$ transmission line.
- Each two cells are combined by a TL with negligible electrical length.
- The required impedance for the two combined cells is 29/2Ω.
- The quarter line's impedance is chosen to transform 100Ω to 29/2Ω.



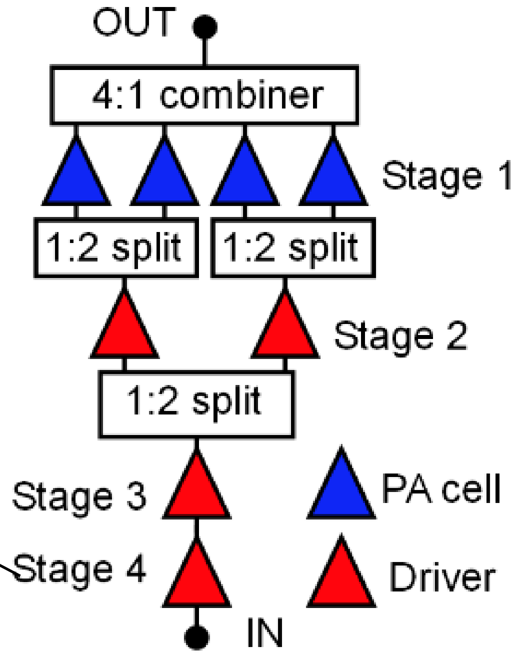
4:1 proposed combiner

Driver Cell Design

- Design is similar to the power cell.
- Architecture uses CB with finite base capacitance.
- Conservative driver scaling ensures hard compression characteristics at the expense of PAE degradation.



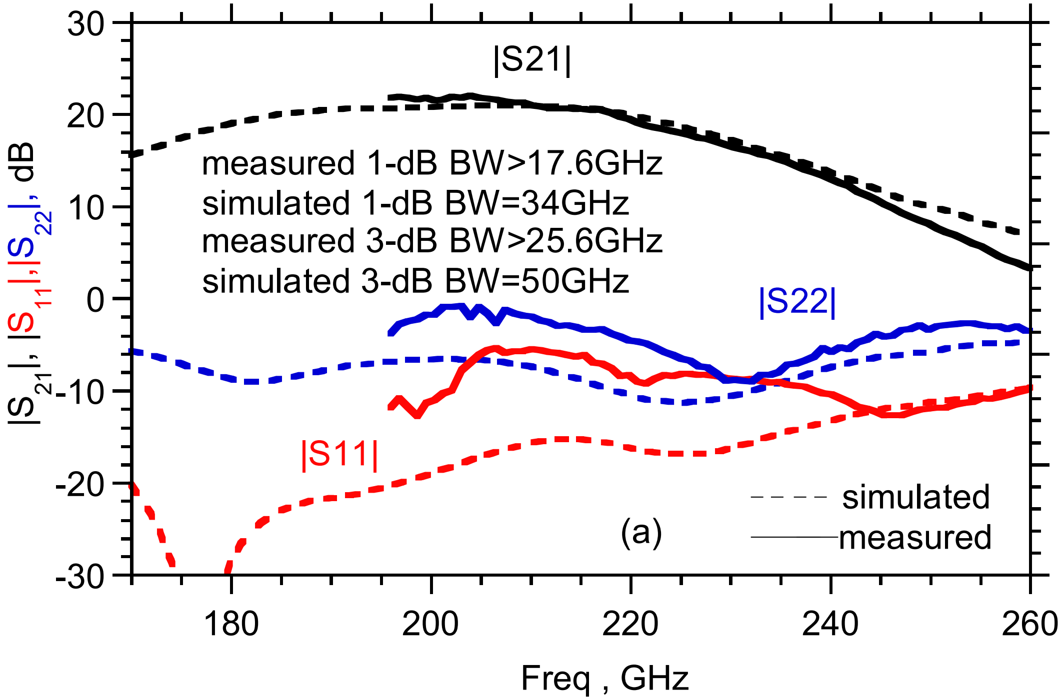
Driver cell



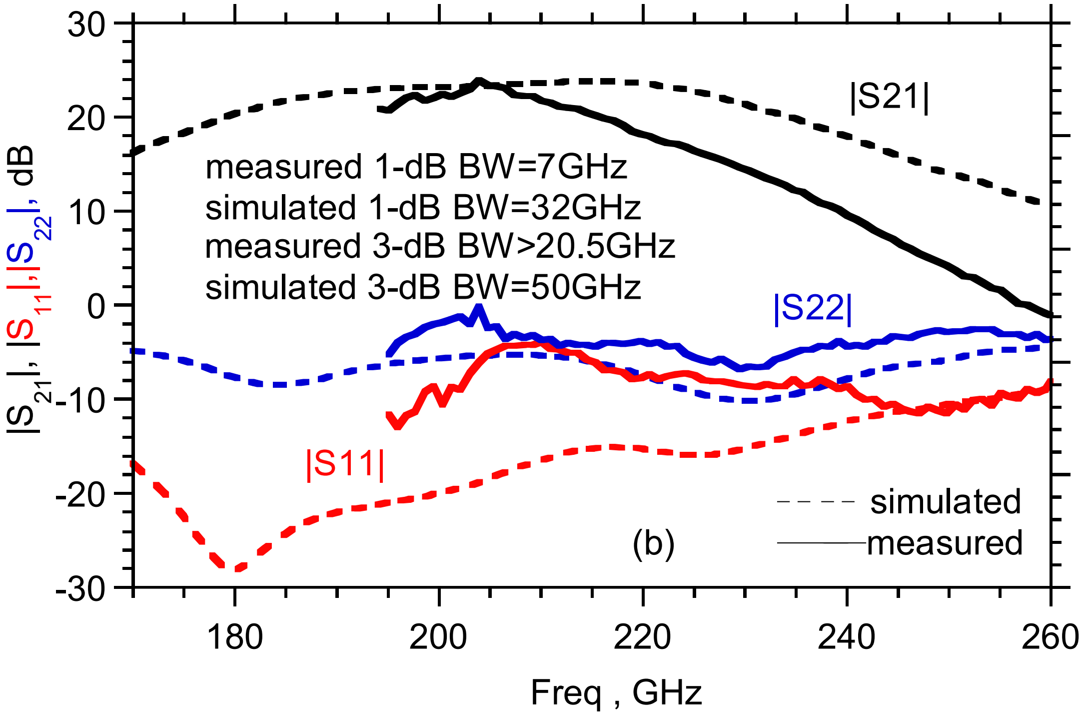
Amplifier block diagram

Measurement Results: s-parameters

- Good agreement at low bias
- Some deviations are observed at higher bias-> maybe heating effect.



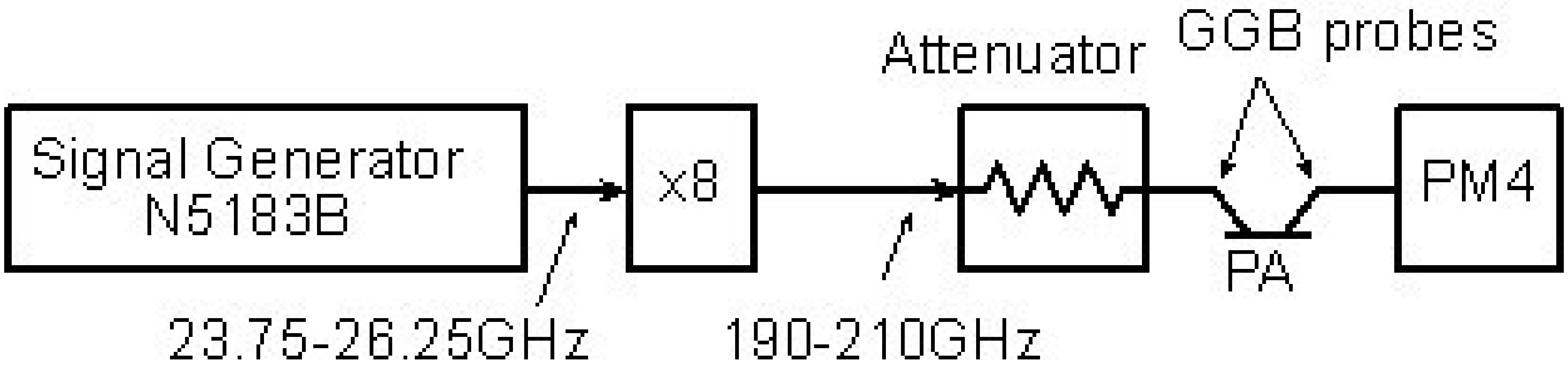
S-parameters at P_{DC}=444mW



S-parameters at P_{DC}=858mW

Power Measurement: literature

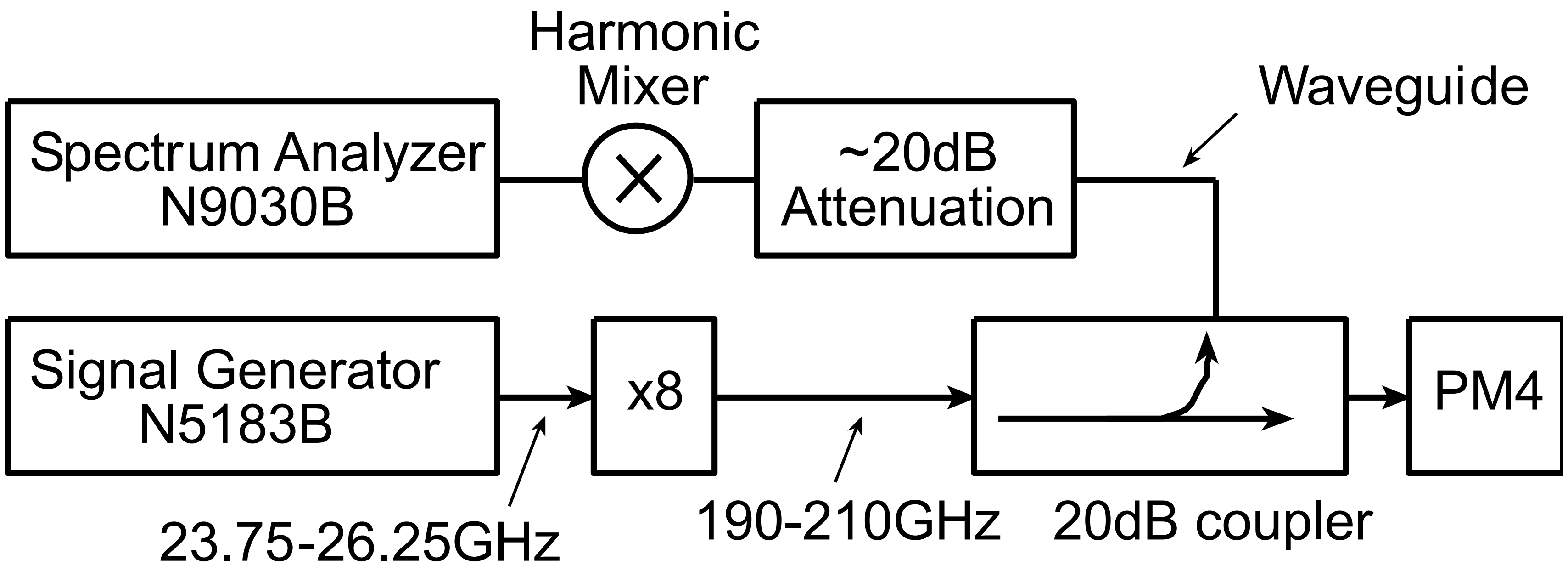
- Conventional measurement: attenuator after a frequency multiplier chain.
- Power sweep: change the attenuator settings.
- Cons
  - The actual input power is unknown-> less accurate results.
  - In many cases, the attenuator is manually changed -> lift the probes and turn off the PA, not convenient.



Conventional power setup

Proposed Approach: setup

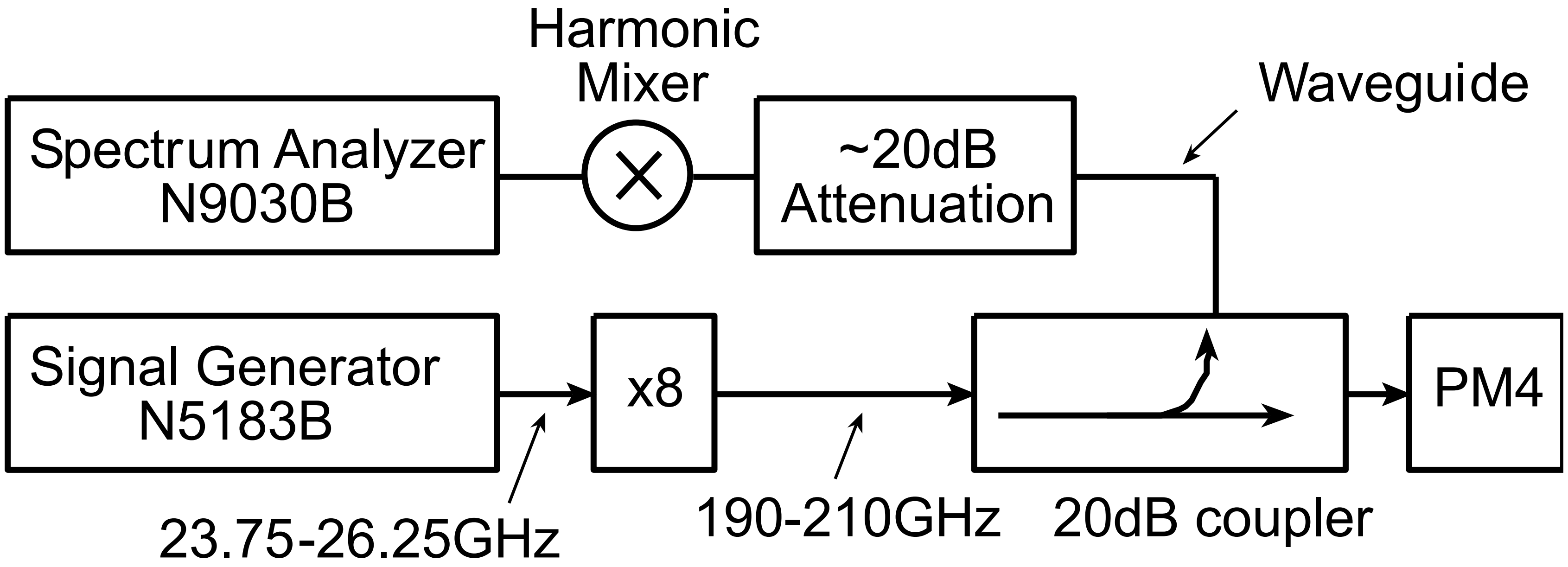
- The VDI's output power is sampled by a coupler and monitored by the spectrum analyzer.
- The spectrum analyzer readings represents the power by adding the appropriate correction factor in the calibration phase.
- Sweep input power: control the signal generator.



Proposed power setup

Calibration phase

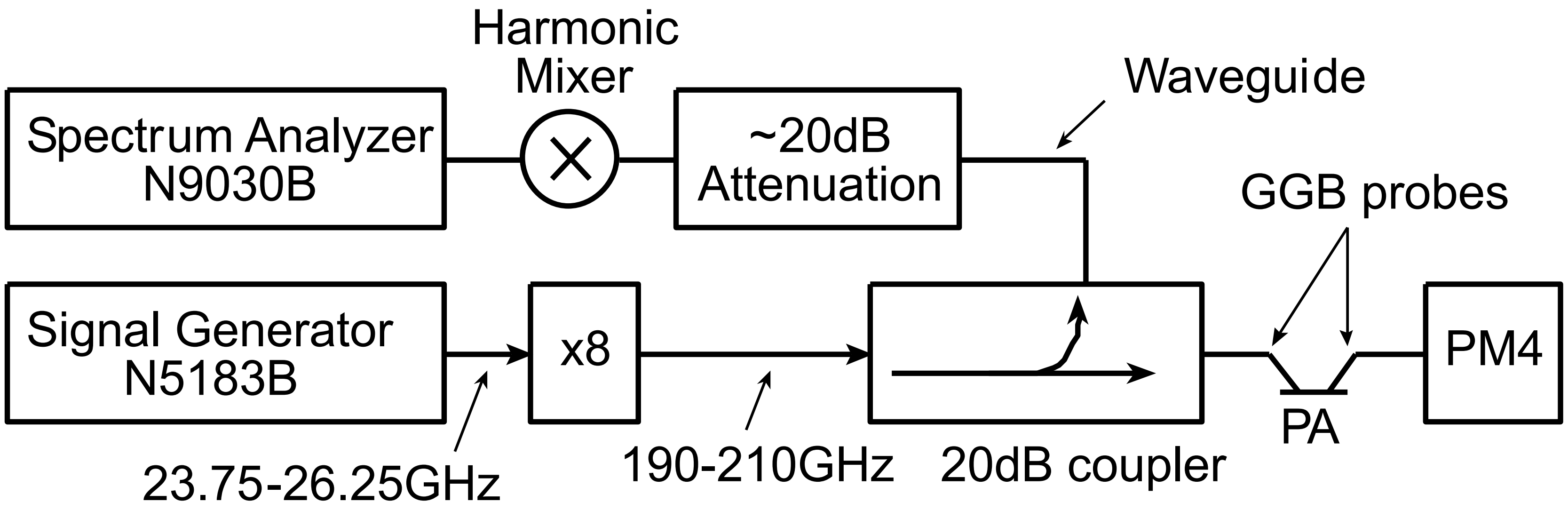
- Record the power difference (dB) between the power meter and spectrum analyzer readings.
- This difference is the correction factor that should be added to the spectrum analyzer readings to represents the actual input power.



Calibration

Measurement Phase

- Sweep the signal generator power.
- Record the spectrum analyzer readings + the appropriate correction factors. This represents the amplifier input power after calibrating the probe losses by through measurements.
- Report the power meter reading.
- The power meter readings represent the amplifier output power after calibrating probe loss.



Measurement

Pros of this measurement approach

- Accurate gain measurement even at very low input power.

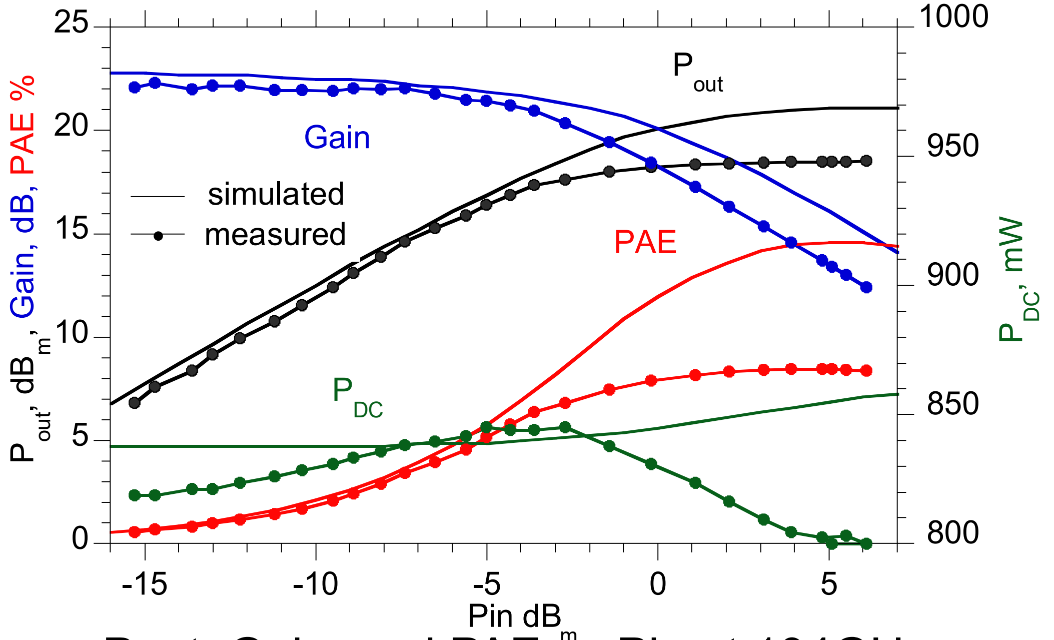
- Power is swept by the signal generator
  -> Extremely convenient since all the measurements are done without lifting the probes or turn off the PA bias.

Power Measurement Results

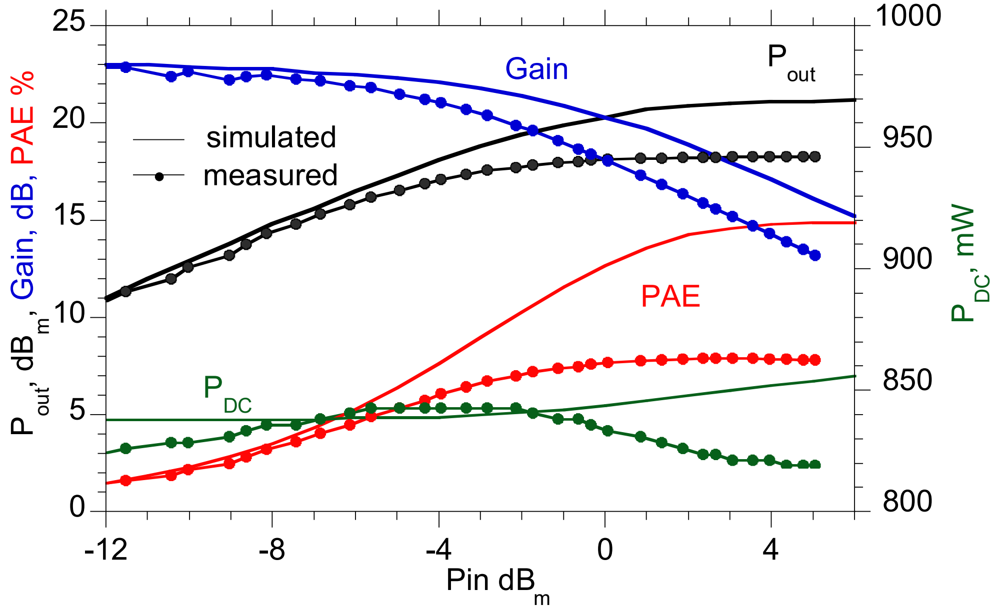
- Many points are recorded at different frequencies.

Freq, GHz	OP_{1dB}, dBm	PAE, % at OP_{1dB}	P_{sat}, dBm	PAE, % at P_{sat}
194	17.4	6.4	18.5	8.5
202	16.6	5.3	18.3	7.9

- Discrepancy between simulations and measurement maybe due to the probe conditions.



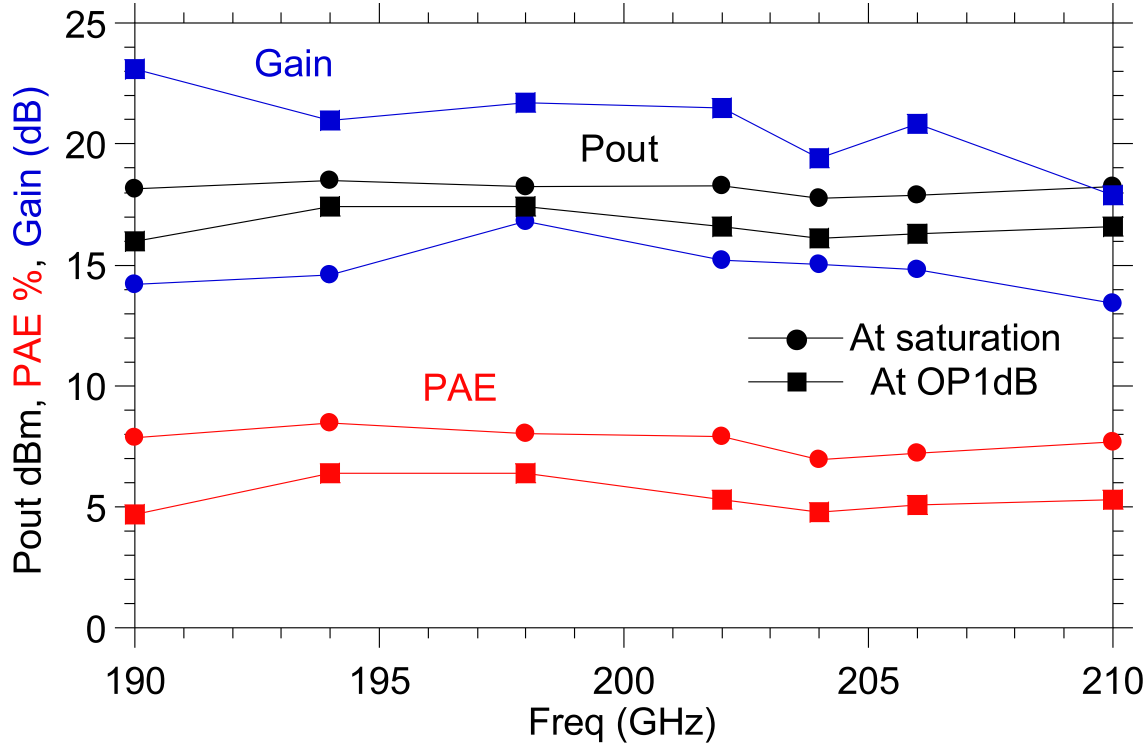
Pout, Gain, and PAE vs Pin at 194GHz



Pout, Gain, and PAE vs Pin at 202GHz

Power Measurement Results

- More points are taken at different frequencies.
- P_{sat}=17.7-18.5dB_m, with PAE=6.9-8.5% over 190-210GHz
- OP_{1dB} =16-17.4dB_m with PAE=4.7-6.4% over 125-150GHz



Measured P_{out} with the associated PAE and gain vs. frequency reported at the peak PAE.

State-of-the-art results

Ref	[7]	[8]	[9]	[10]	This work
Freq, GHz	204	190	180-260	190.8-244	190-210
P_{sat}, dBm	18.0	11	17.5-21.5	16.2-18.9[a]	17.7-18.5
Gain at P_{sat} (dB)	16.5	19.2	13-17.5	19-22[a]	13.4-16.8
PAE at P_{sat}%	4.8	9.6	5.1	3.3-6.1	6.9-8.5%
OP_{1dB}, dBm	15.5[a]	3	17.5	16.1-17.16[a]	16-17.4
PAE at OP_{1dB}%	3.2[a]	2	2.1[a]	2.3-3.0[a]	4.7-6.4
Gain at OP_{1dB}	15.5[a]	27[a]	23.5[a]	23.8-35.0[a]	17.9-23.1
BW_{3dB}, GHz	>25	26	18[a]	53	>20.5
Size (mm^2)	0.91	0.45	1.8	1.54	1.14
P_{DC} (mW)	1180	970	2620	1270	814
P_{sat}/Area mW/mm^2	69.2	28.2	77.9	50.6	62.1
OP_{1dB} /Area mW/mm^2	39	28	31.2	33.8	48.2
Technology	130nm InP	250-nm InP HBT			

- This work shows a record PAE at OP_{1dB}

Summary

- Demonstration of record PAE at G-band
- Communication transmitter requires careful attention to the performance at OP_{1dB}
- Key features for highest efficiency at OP_{1dB}
  - –Proper cell topology: Capacitively linearized common base
  - –Higher OP_{1dB}, and PAE
  - –Driver scaling sustains good PAE
- Compact and low loss transmission line network

Acknowledgement

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Thank You

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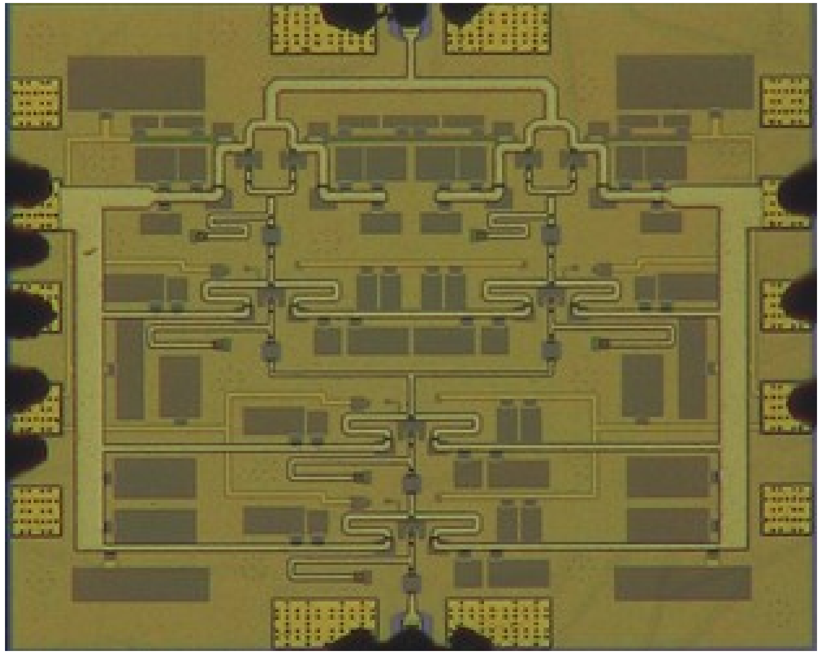
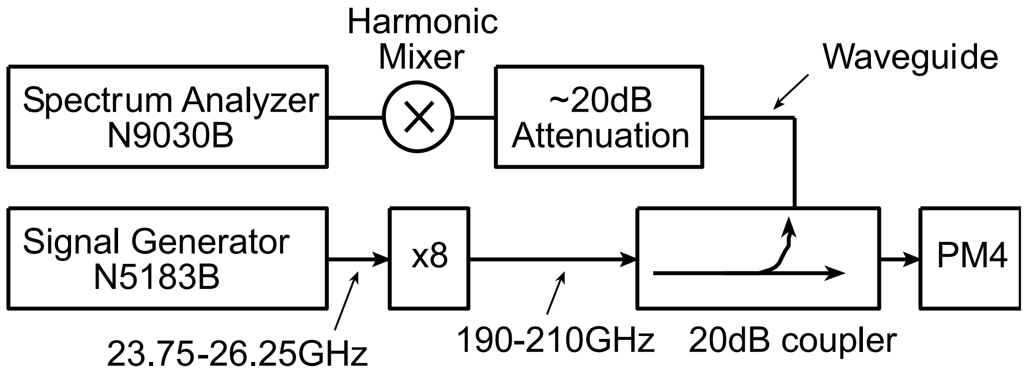
DC Bias Lines and Power Supply Oscillations

- Only two independent DC supplies -> reduce the bias complexity.
- one supply biases all stages' collectors and the second biases the stages' bases.
- There are many feedback loops-> potential stability problems.
- We noticed a potential oscillation problem at low frequencies (~GHz and lower) in earlier designs.
- The low frequency oscillations are not adequately modeled and does not show up in simulations.
- In this design, we added many bypass capacitors with series resistors to avoid out of band oscillations.
- There is no indication for oscillations.

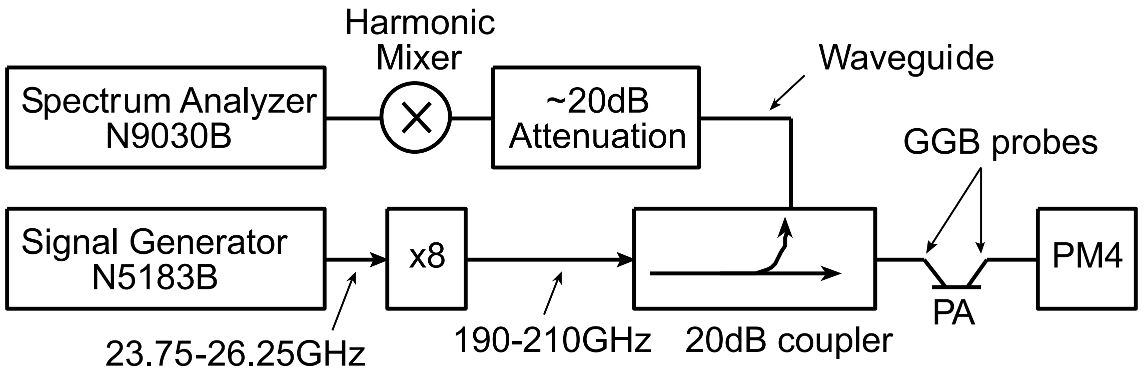


Measurement accuracy

- The dynamic range of the power sweep is defined as follows:
  - The minimum input power: limited by the spectrum analyzer noise level.
  - Spectrum analyzer with reasonable noise levels shows smooth gain curves at low input power-> get accurate results to accurately report OP_{1dB}.
  - The maximum power: limited by the harmonic mixer saturation limit.



Calibration



Measurement

Measurement accuracy

- Probe losses are calibrated by through measurement.
- Old probes show non-50Ω impedance which degrades the output power.
- So, the probes may contribute to higher losses than the one measured in the through measurement.
- We did the measurement with an old probe pair, and we believe that the results could be improved by a newer one.