20.5 An Ultra-Low Power 2.4GHz RF Transceiver for Wireless Sensor Networks in 0.13µm CMOS with 400mV Supply and an Integrated Passive RX Front-End

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Wireless mesh sensor networks are emerging as an attractive solution for home automation, industrial monitoring, and many other applications. Improved reliability and lifetime are critical to widespread adoption of these networks. To replace wired devices, wireless nodes must offer reliable data delivery in the presence of high-power jammers, such as cordless phones and WLAN, while delivering at least 10m indoor range and lifetimes measured in years from small batteries or scavenged power. Lifetime requirements constrain average power consumption to around 10µW, resulting in low radio duty-cycles, and reliability requirements dictate that radios must be highly linear and frequency agile to avoid interference. While computation and analog-to-digital conversion can be performed for only tens of pJ per 8b operation [1, 2], wireless data transmission for sensor networks has required 25 to 350nJ/b (TX and RX included) [3, 4, 5], making RF the key to battery lifetime extension.

In this paper, an RF transceiver intended for the 2.4GHz ISM band capable of 3nJ/b communication with 92dB link margin and no external RF passives is presented. The transceiver operates from a 400mV supply, permitting the use of a single solar cell power source. To accommodate the 400mV supply while maintaining good NF and linearity at minimum power, a differential, passive RX front-end topology is developed (Fig. 20.5.1). The integrated RX consumes from 200 to 750µW of power and features: a passive front-end, a back-gate coupled quadrature VCO (Fig. 20.5.2) [6], and a bandpass baseband with a piecewise logarithmic RSSI. The TX utilizes a differential PA driven directly from the cross-coupled VCO tank (Fig. 20.5.1) and binary FSK is accomplished by modulating the VCO as demonstrated in [3]. A single integrated LC matching network interfaces both TX output and RX input to a 50Ω differential impedance. A block diagram of the transceiver is given in Fig. 20.5.3 and a performance summary is given in Fig. 20.5.4.

First-order analysis similar to that in [7] shows that energy/(bit·m) will be minimum for this system for a link margin of 86 to 96dB, depending on path-loss conditions. Data rate is chosen to minimize energy/bit while maintaining link margin. At very low data rates, and thus low noise bandwidth, the link margin may be achieved at minimum power but the energy/bit will be quite high due to the power required to sustain the RF VCO. On the other hand, since these radios have low duty cycles and relatively small data payloads, very high data rates will also result in high energy/bit dominated by PLL settling and time synchronization with the network. A data rate of 300 to 500kb/s is chosen as a tradeoff.

In RX, the LC matching network provides 15dB of passive voltage gain and matches the passive mixer input to 50Ω. Since the RX front-end is passive, use of differential circuits did not incur a power penalty. The RX operates with either single-phase or quadrature downconversion. Quadrature generation is accomplished with a back-gate coupled quadrature VCO (Fig. 20.5.2). To provide adequate mixer drive subject to the 400mV supply headroom constraint, the mixers are driven directly from the VCO tank because the tank output voltage swings about the supply rail. Under typical VCO swing and biasing, the NF is dominated by the first bandpass amplifier stage following the mixer. The RX offers a wide NF/power consumption tradeoff and achieves an NF of 6.7dB and an IIP3 of -7dBm while consuming 330µW (Figs 20.5.4 and 20.5.5).

Capacitors at the mixer outputs place a lowpass RC pole at 1MHz. The subsequent active filter stages consist of pairs of linearized CMOS inverters operating differentially with a bandpass response. A 600 to 900mV supply sourcing less than 5µA is needed for dc biasing and this could be generated efficiently with an integrated capacitive step-up converter as in [4]. The passband extends from 200 to 750kHz and the outputs of all four stages following the mixers ac-couple to FET amplitude detectors. The detector output currents from all stages are summed to provide a piecewise logarithmic RSSI.

The TX comprises a differential PA loaded with an on-chip matching network and driven directly from the cross-coupled VCO tank. Direct VCO drive allows the VCO to tune out PA input capacitance and reduce current [3] while delivering large voltage amplitude for class-C operation by swinging about the supply rail. The choice of binary FSK modulation permits a simple, ultra-low power TX architecture utilizing direct VCO modulation with some sacrifice of spectral efficiency.

With an inductively loaded differential PA, an output power up to +8dBm would be achievable from the 400mV supply. However, analysis reveals that, for this system, power output of between -2 to -9dBm minimizes energy/(bit·m) [7], implying a swing of only 130 to 260mV on a 50Ω load. To attain high PA efficiency with low power output, the integrated resonant matching network boosts the PA load impedance (Fig. 20.5.1). The PA efficiency is at least 44% for output power between -7 and -5dBm and the global efficiency is 30% at -5dBm power output (Fig. 20.5.6).

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[7] B. W. Cook, A. Molnar, and K. Pister, “Low Power RF Design for Sensor Networks,” *RFIC Symp.*, pp. 357-360, June, 2005.

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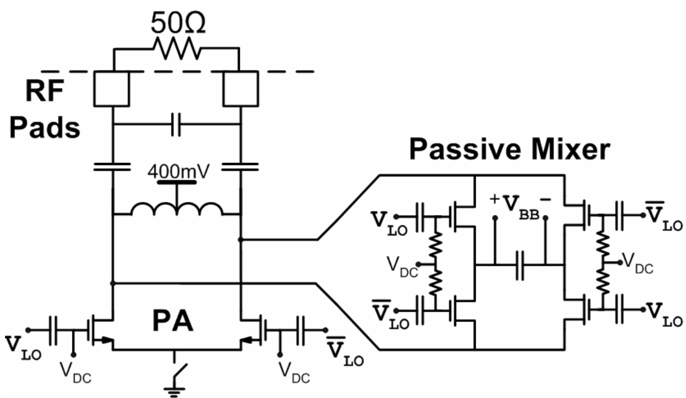

Figure 20.5.1: Passive RX front-end and PA schematic.

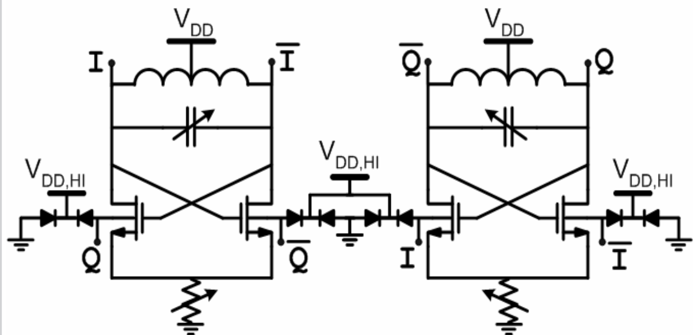

Figure 20.5.2: Back-gate coupled quadrature VCO schematic.

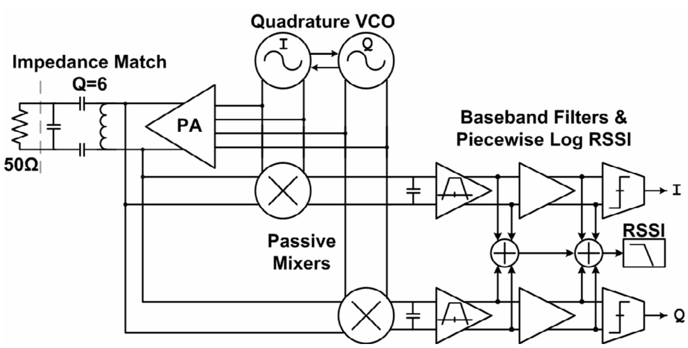

Figure 20.5.3: Transceiver block diagram.

Overall		Value	
Supply Voltage	Min/Typ/Max	360/400/600	mV
2-FSK Deviation	Min/Max	300/1000	kHz
RX			
Power Consumption	Min/Max	200/750	μW
Noise Figure	Min/Max	5.1/11.8	dB
IIP3	Typ.	-7.5	dBm
TX			
Power Consumption	Min/Max	700/1120	μW
Output Power	Min/Max	140/320	μW
PA Efficiency	$200 < P_{OUT} < 300$ μW	>44	%
VCO			
Power Consumption	$Min_{I\ Only}/Max_{I+Q}$	160/700	μW
Frequency	Min/Max	1.95/2.38	GHz
Quadrature Mismatch	Meas. ΔΦ at I&Q Mixer Out	|ΔΦ-90| < 5	deg
Phase Noise @1MHz	@ P_{VCO} = 270 μW	-106	dBc/Hz

Figure 20.5.4: Summary of measured results.

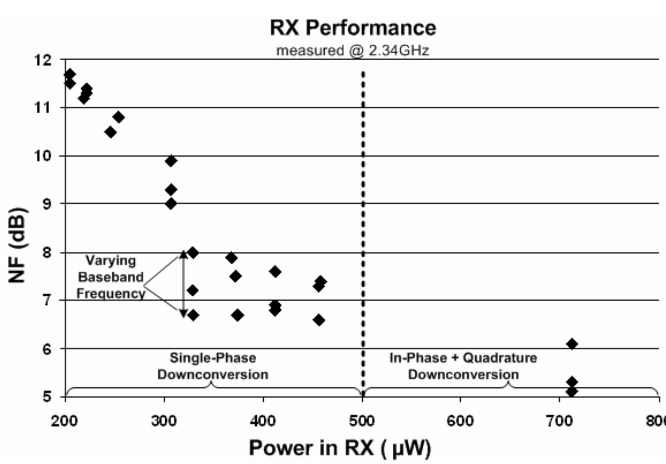

Figure 20.5.5: Measured receiver NF versus power consumption.

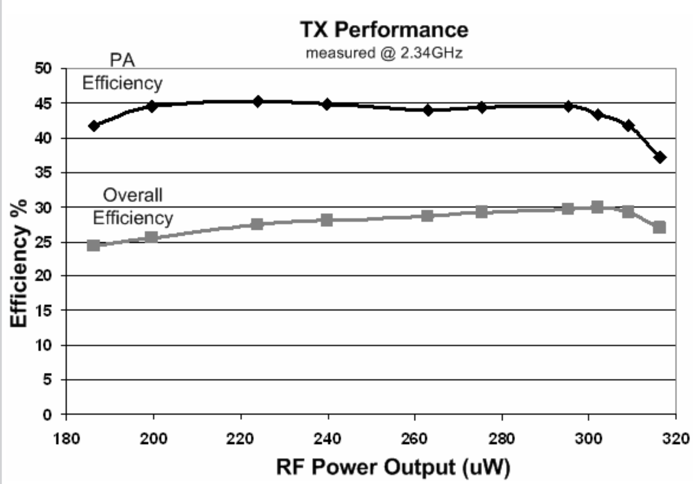

Figure 20.5.6: Transmitter and PA efficiency versus power output.

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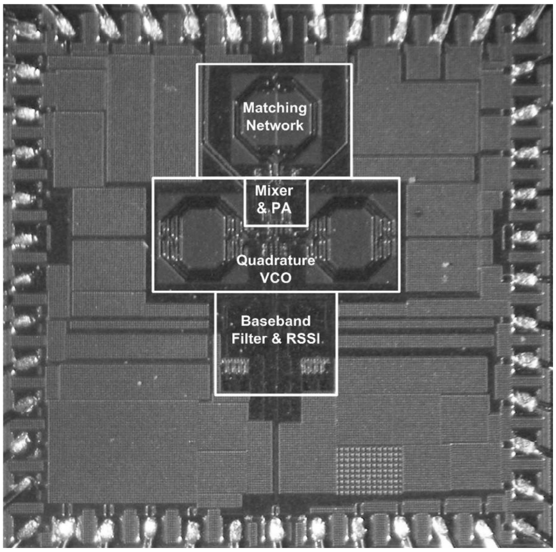
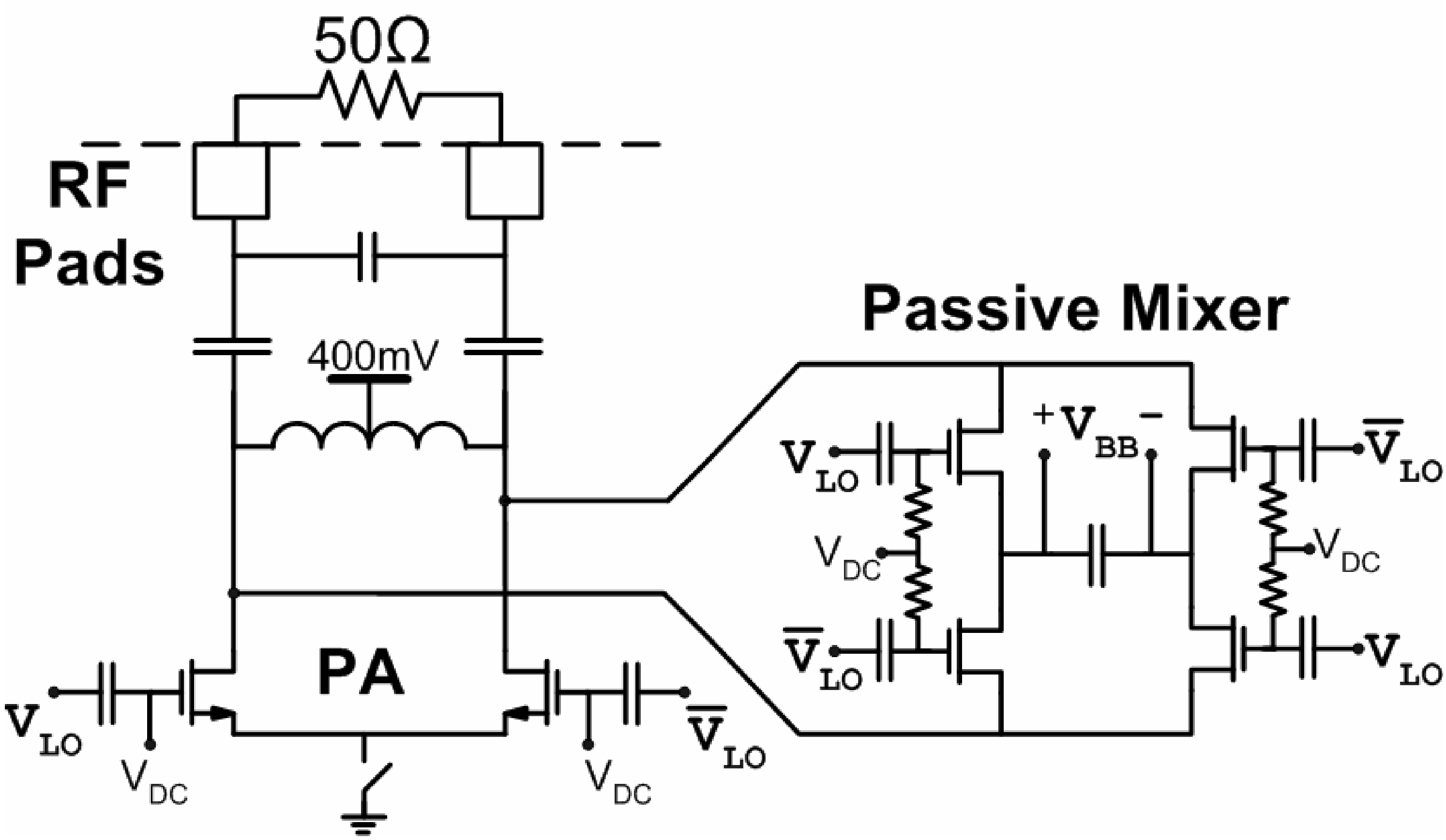


Figure 20.5.7: Die micrograph.



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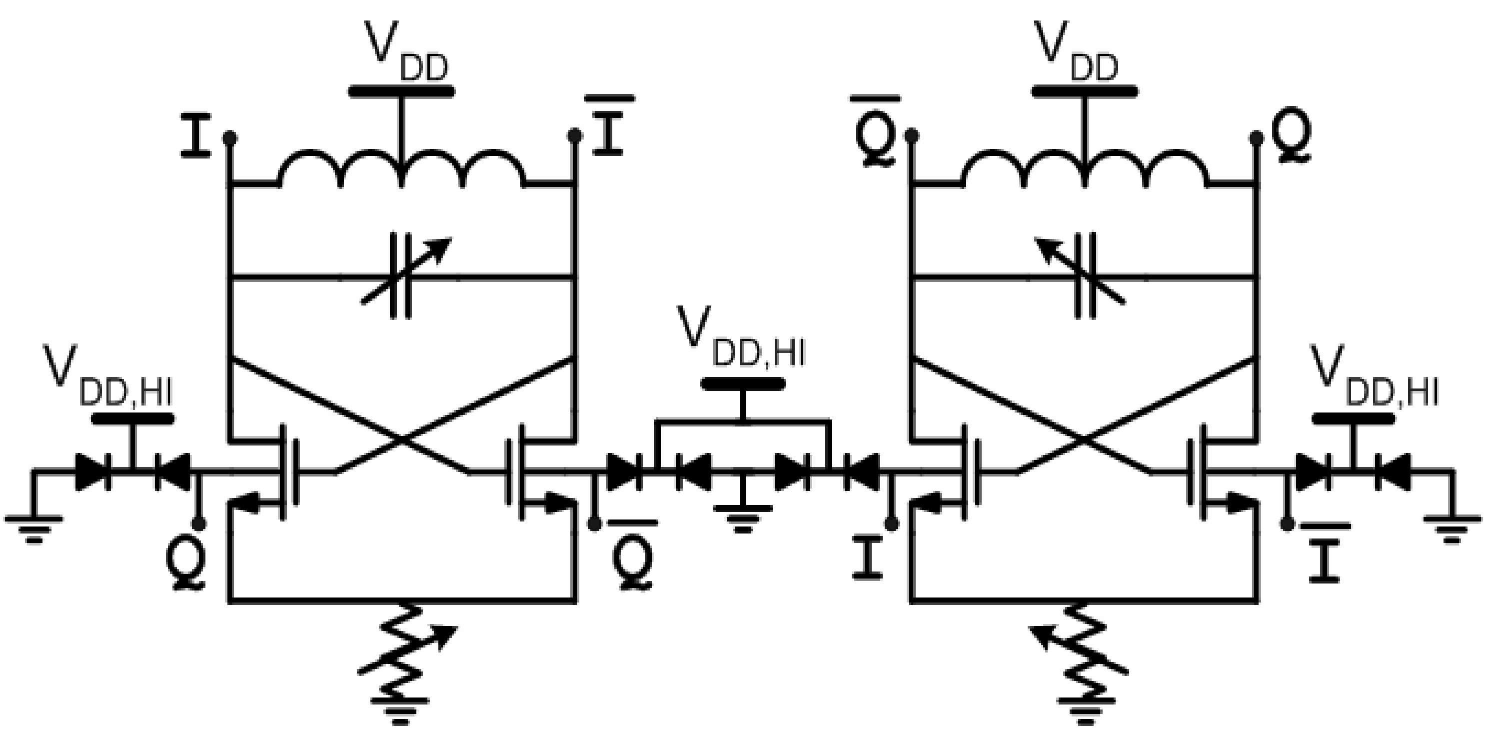
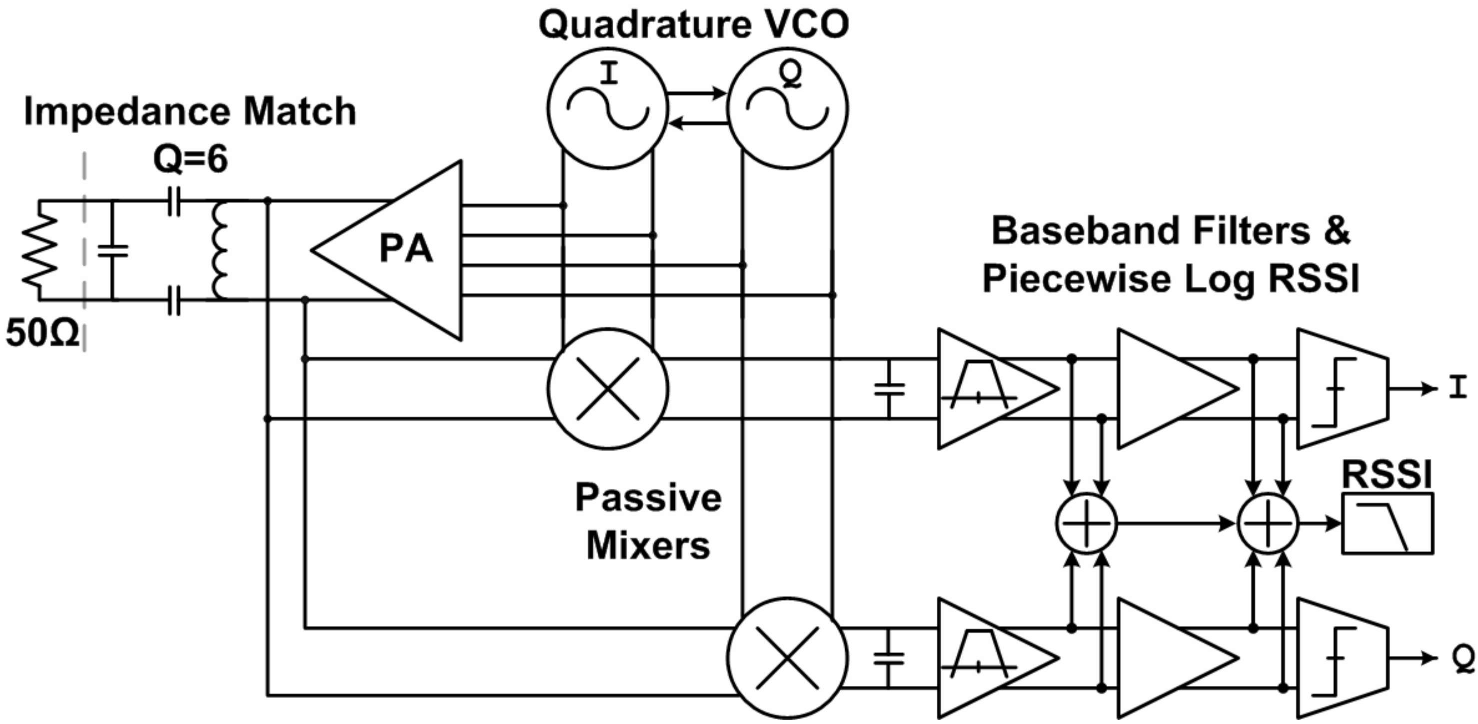


Figure 20.5.2: Back-gate coupled quadrature VCO schematic.



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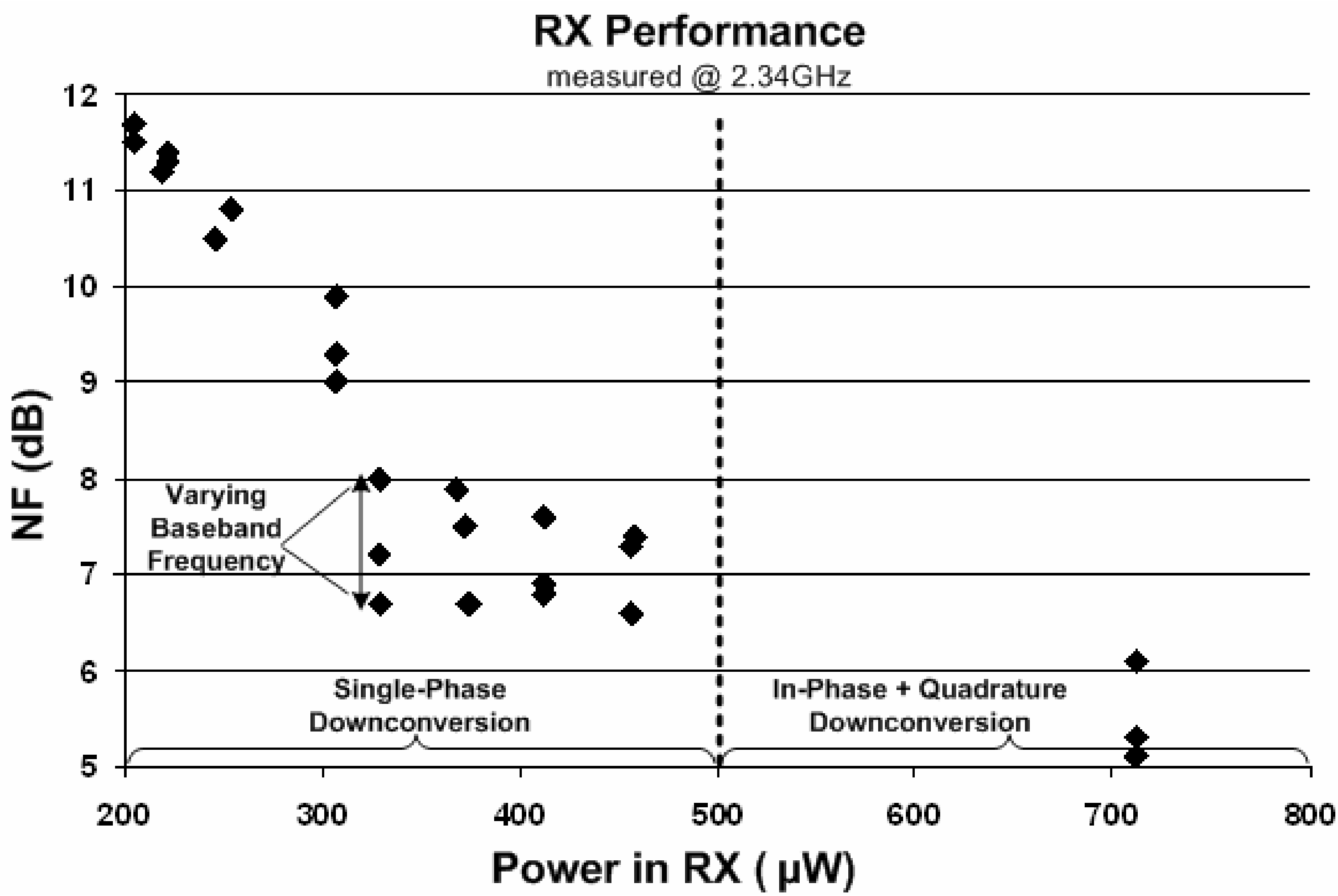

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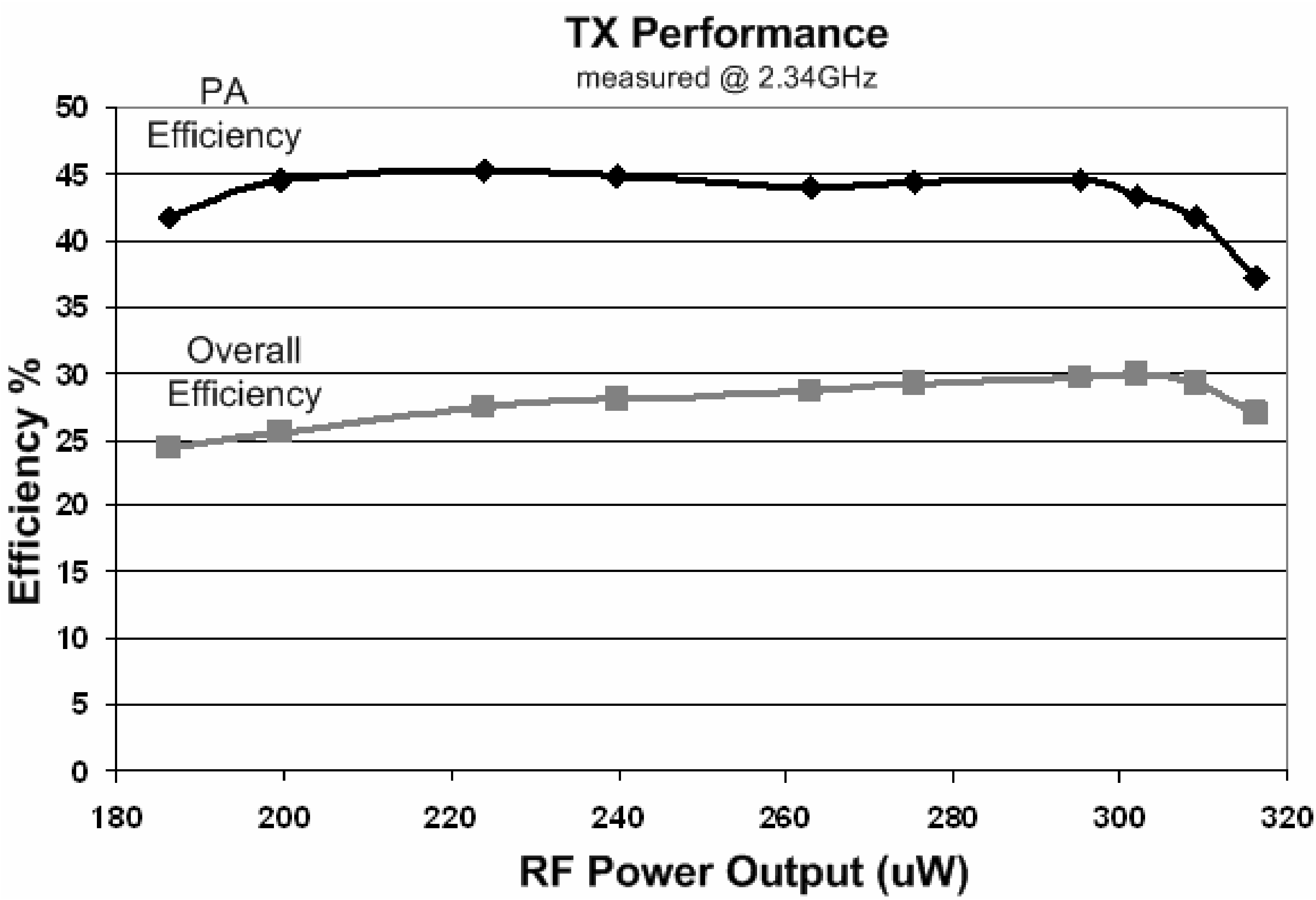
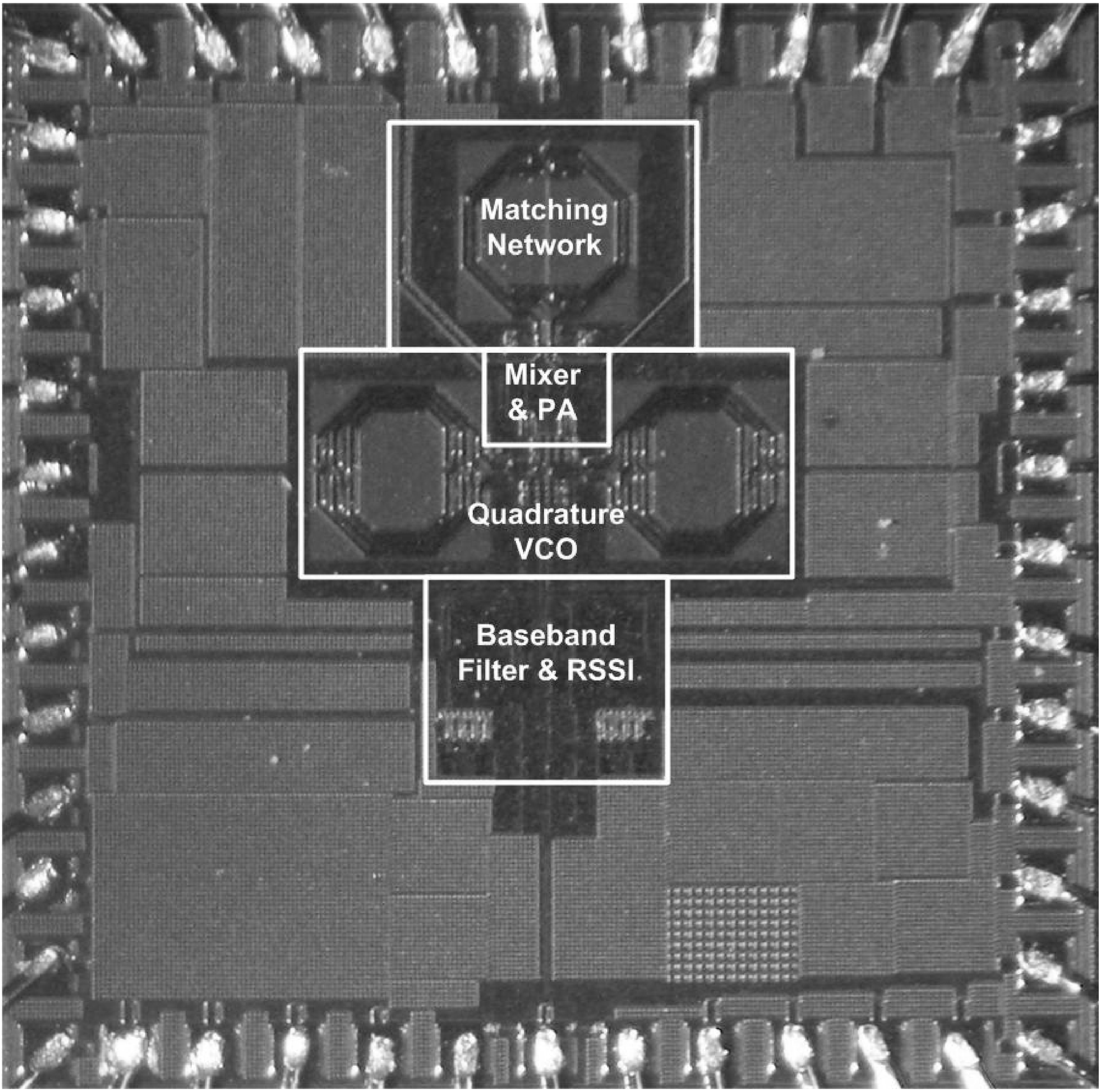


Figure 20.5.6: Transmitter and PA efficiency versus power output.



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