A maximum efficiency tracker periodically samples the peak voltage of \( V_C \), which is digitized with an 8b ADC (Fig. 21.5.2). Given this information about \( P_{IN} \), an on-chip digital-signal processor (DSP) sets 3 parameters to maximize \( \eta_{RESO} \), \( I_{BIAS} \), and \( F_{DET} \). The optimal \( N_{RESO} \) across varying \( P_{IN} \) levels is measured (Fig. 21.5.4). At \( P_{IN} = 600\text{mW} \), the optimal \( N_{RESO} \) is 10, and it decreases at higher \( P_{IN} \). This measured result confirms that for low \( P_{IN} \), resonating for multiple cycles helps build up LC tank energy, while for high \( P_{IN} \), the large \( I_{IND} \) results in high conduction loss in \( M_{RE} \), limiting gain from high \( N_{RESO} \).

The limited bandwidth of the ZCD results in a switching-voltage error, \( V_{SET} \). As a result, \( C_{RX} \) has \( C_{RXVerr}/2 \) energy at the end of \( M_{RE} \), not the ideal \( 0 \). This energy is wasted by charge redistribution in \( M_{CH} \), and conduction loss at the next \( M_{RE} \). Increasing \( I_{BIAS} \) reduces this loss by improving ZCD bandwidth, but increases its energy consumption. With fixed \( I_{BIAS} \), \( V_{SET} \) increases for high \( P_{IN} \), and thus a higher \( I_{BIAS} \) is required for higher \( P_{IN} \). Similarly, a mistimed transition from \( M_{RE} \) to \( M_{CH} \) leads to energy loss, either by incomplete transfer of \( E_C \) to the battery (when switched too early) or by a transfer of battery energy into \( L_{RX} \) (when switched too late). Charging time \( (\approx L_{RX}/V_{BAT}) \) is shorter for lower \( P_{IN} \), and thus higher \( F_{DET} \) for the \( V_{BAT} \) detector is required at lower \( P_{IN} \). As the optimal \( I_{BIAS} \), \( V_{SET} \), and \( F_{DET} \) values depend on \( P_{IN} \), the DSP divides \( P_{IN} \) into sub-regions and assigns optimal values accordingly.

Another advantage of current-mode charging is the reduced design complexity due to elimination of precise voltage regulation. In voltage-mode charging a mm-sized thin-film battery \( [9] \) requires a charging voltage accuracy of ±3.6% from a nominal voltage. Given process-dependent \( V_{TH,RECT} \), a DC-DC converter requires wide input range, wide conversion ratio, and input voltage detection. On the contrary, charging current requires no regulation as long as the resulting voltage does not exceed the battery breakdown voltage, reducing charging overhead and enabling low \( P_{IN} \) operation.

The system was fabricated in 0.18μm CMOS and includes a Coilcraft 4513TC receiver coil and 1.4nf off-chip capacitor. Measured \( P_{IN,MIN} \) (600mW) is 3.9x lower than the state-of-the-art work \( [5] \) and 13x lower than \( [8] \), which uses the same size coil. This sub-μW \( P_{IN} \) becomes harvestable when \( N_{RESO} > 7 \). Maximum \( \eta \) is 61.2% at \( P_{IN} = 2.8\text{μW} \) with \( N_{RESO} = 4 \). The energy in the LC tank increases with larger \( N_{RESO} \), but is upper-bounded by increasing conduction loss. Switching energy per 1 charging event remains the same regardless of \( N_{RESO} \). However, as \( ZCD \) energy consumption increases with growing \( N_{RESO} \), an optimal \( N_{RESO} \) arises. With a 20mW transmitter the maximum separation of TX/RX coils is 8.5cm in air. Identical performance is measured through 3cm of bovine tissue and 5.5cm air; this is expected since theoretically tissue absorbs negligible power at 50kHz. This result fits our target application where an implantable system is charged by an external transmitter under the energy exposure limits of human tissue. Oscilloscope waveforms in Fig. 21.5.5 show \( V_C \) building up in \( M_{CH} \); \( V_{BAT} \) is captured, as is \( V_C \) rising past \( V_{SET} \) to allow charging and then returning back to \( M_{RE} \). This work shows the lowest \( P_{IN,MIN} \) and maximum of \( \eta \) of 61.2% at >11x lower \( P_{IN} \) than state-of-the-art works in Fig. 21.5.6. Design area is 0.54mm\(^2\) (Fig. 21.5.7).

References:
Figure 21.5.1: Conventional wireless power transfer / battery charging system (top) and proposed wireless power receiver and current-mode charger with optimal resonant cycles (bottom).

Figure 21.5.2: A system block diagram with operating waveforms.

Figure 21.5.3: A detailed circuit diagram of the wireless power receiver controller.

Figure 21.5.4: Measured power efficiency (top, left), optimal number of resonant cycles (top, right), energy transferred per cycle, saved in LC tank, and consumed at 1.2V (bottom, left), and power efficiency (bottom, right).

Figure 21.5.5: Waveforms measured by oscilloscope.

Figure 21.5.6: Performance summary and comparison table.
Figure 21.5.7: Micrograph of 0.18µm test chip (0.68mm × 0.8mm).