Hybrid-Switched-Capacitor-Resonant DC-DC Converter for LED Driver Application

Chengrui Le

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Columbia University in the City of New York

Berkeley University of California

CUNY The City University of New York

Texas Instruments

Outline

- Introduction
  - Motivation and challenges for better LED drivers
- Solutions
  - Take advantage of capacitors, new architecture combining L &C, capacitive isolation, integration, chip-stackable and expandable module
- The Hybrid-Switched-Capacitor-Resonant converter
- IC implementation
- Measurement results
- Integration with thin film Metacapacitors
- Conclusions

Building Better LED Drivers

- **Solid state lighting**: efficient, environmental friendly, and affordable
- **LED drivers**: Current regulation, power factor correction, galvanic isolation, dimming
- **Goals**:

✓ Efficiency

✓ Cost

✓ Size

✓ Life

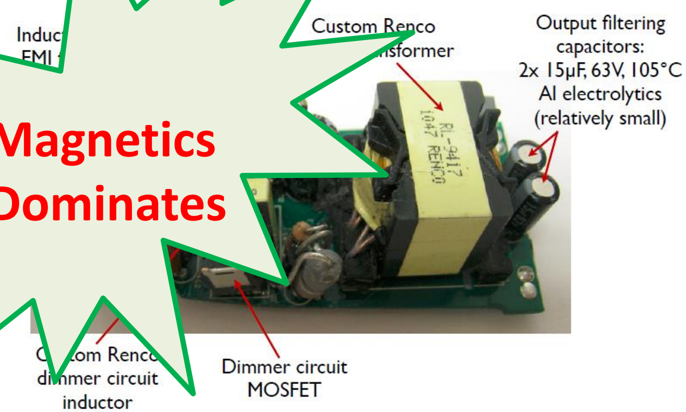
Transformers

Electrolytic Caps

Solutions

1. Architecture with lower V-A product
   - Fundamental elements: Switches & Passives
   - Switches: larger I — R_{ON} ↓; larger V — V_{max} ↑ } Larger device, More parasitics
   - Passives: to pass larger I or *Charge* with lower lost; to stand larger V } Larger device, Higher cost
2. Better passive components
   - Higher energy density, lower cost, longer life, integration, high frequency performance…
3. L- C resonance
   - Parasitic cancellation
   - Lossless power regulation
   - Isolation

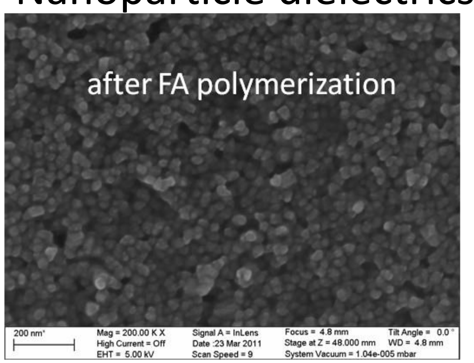
Magnetics Dominates



Take Advantage of Capacitors

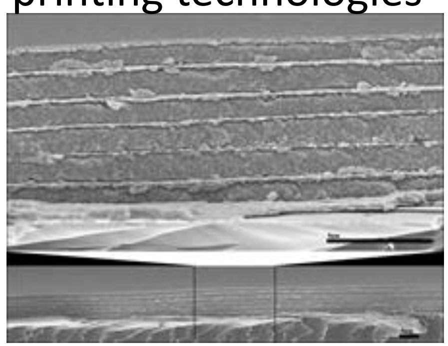
- Switched-capacitor (SC) topology:
  - Lower V-A rating for both individual and over all components. [Seeman, M.D., COMPEL 2010]
  - Multilevel architecture: modular design & reconfiguration.
- High energy density capacitors:
  - high frequency, low loss, pintable thin-film Metacapacitors.
- Multilevel output L-C resonant network
  - Zero Voltage Switching (ZVS).
  - Lossless current regulation.
  - Energy merging and magnetic reuse.
  - Capacitive galvanic isolation.

Self-assembling Nanoparticle dielectrics



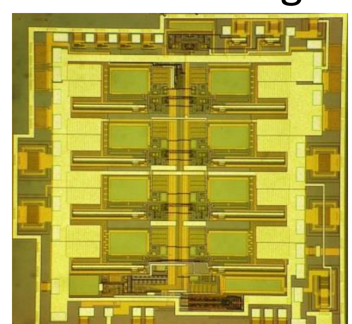
O' Brien (CUNY)

Scalable capacitor printing technologies



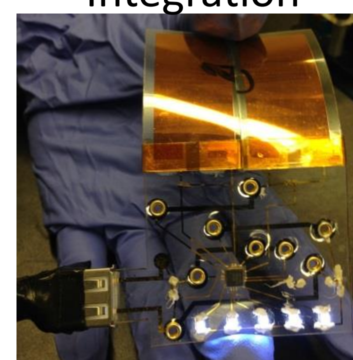
Steingart (Princeton)
Leland (CUNY)

Analog power circuits And IC design



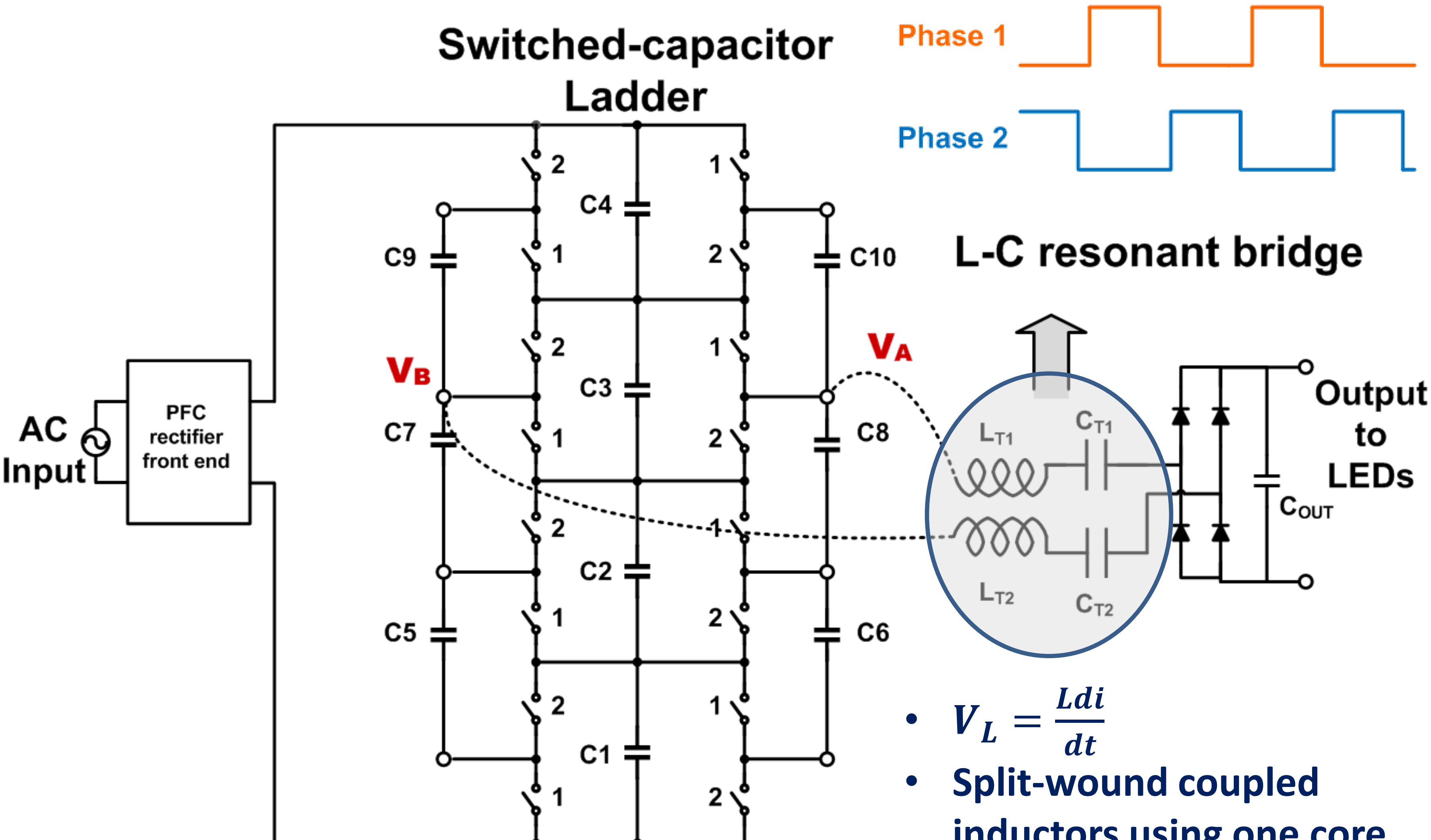
Kinget, Sanders
Columbia, Berkeley

Novel device Integration



Kymissis (Columbia)

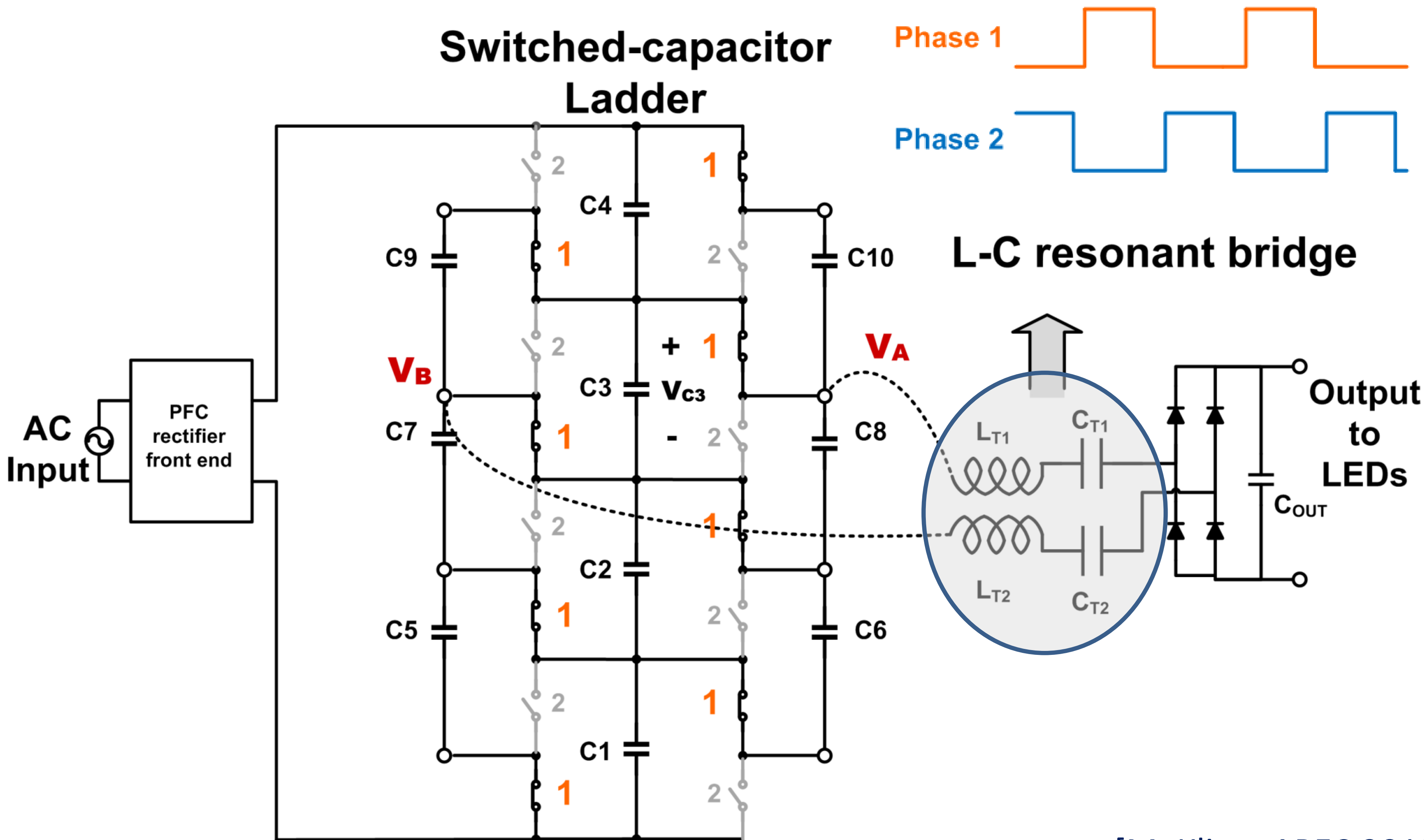
Hybrid-switched-capacitor-resonant LED driver



- $V_L = \frac{Ldi}{dt}$
- **Split-wound coupled inductors using one core**

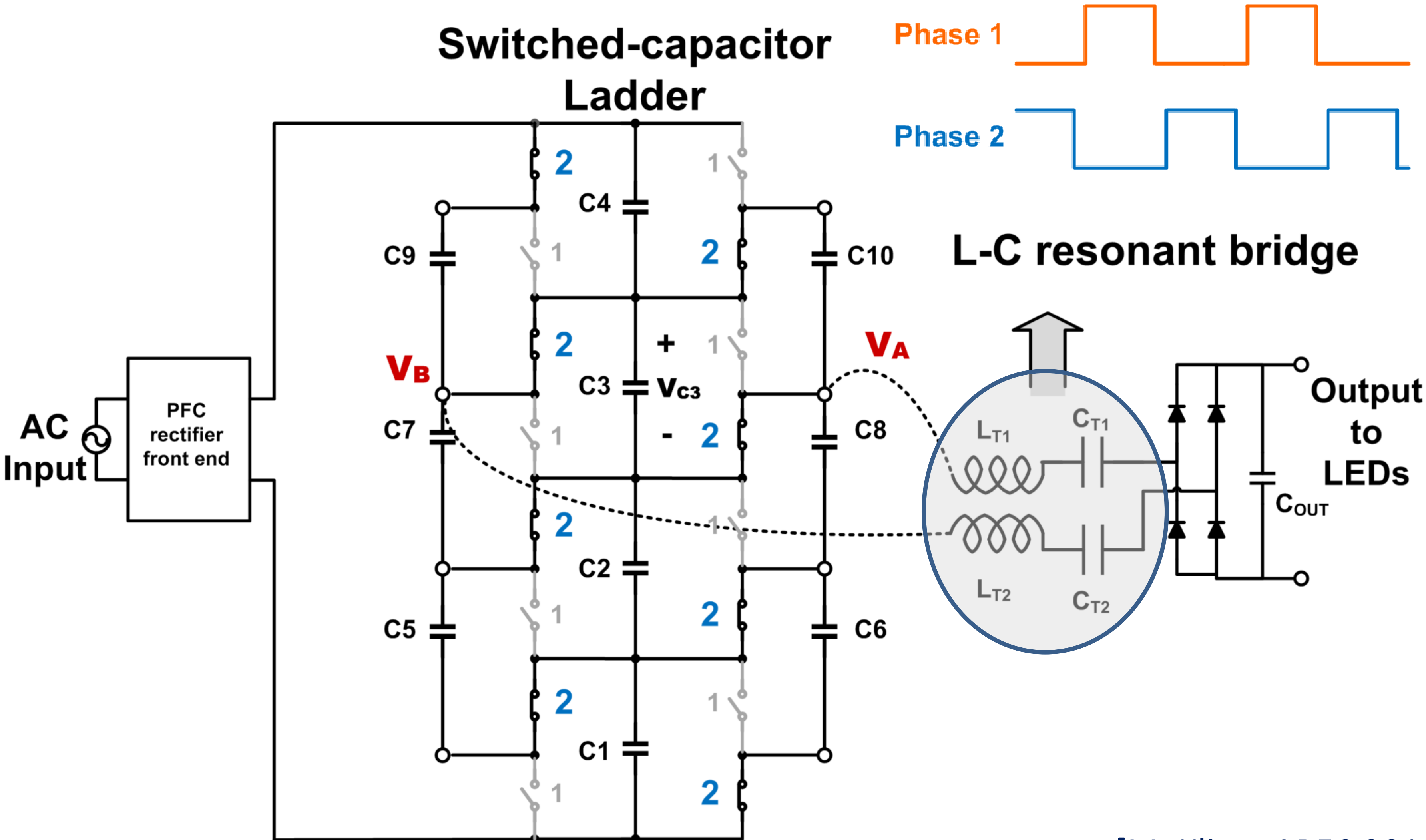
[M. Kline, APEC 2012]

Hybrid-switched-capacitor-resonant LED driver



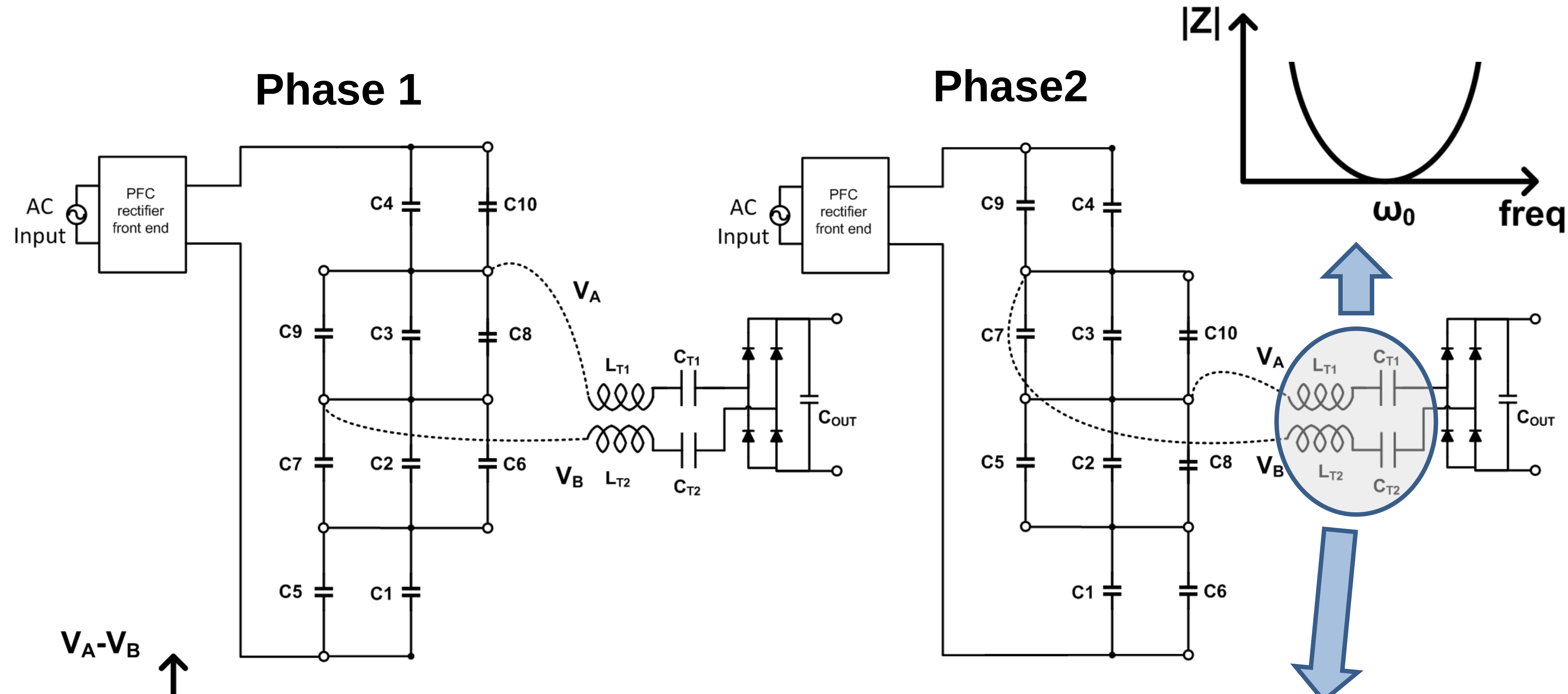
[M. Kline, APEC 2012]

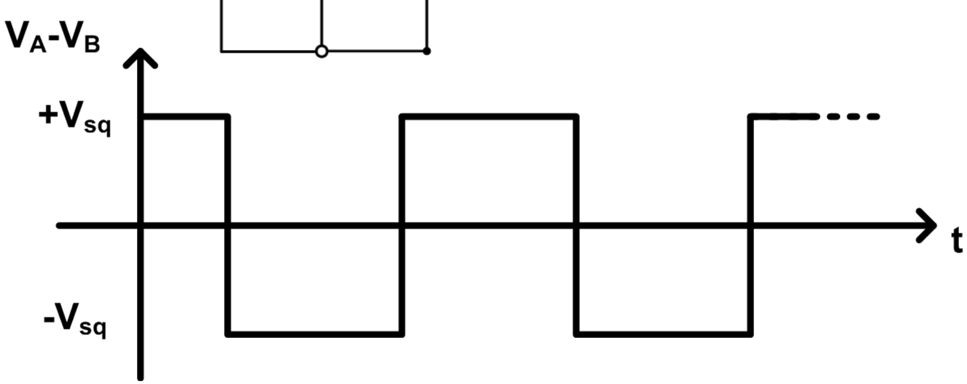
Hybrid-switched-capacitor-resonant LED driver



[M. Kline, APEC 2012]

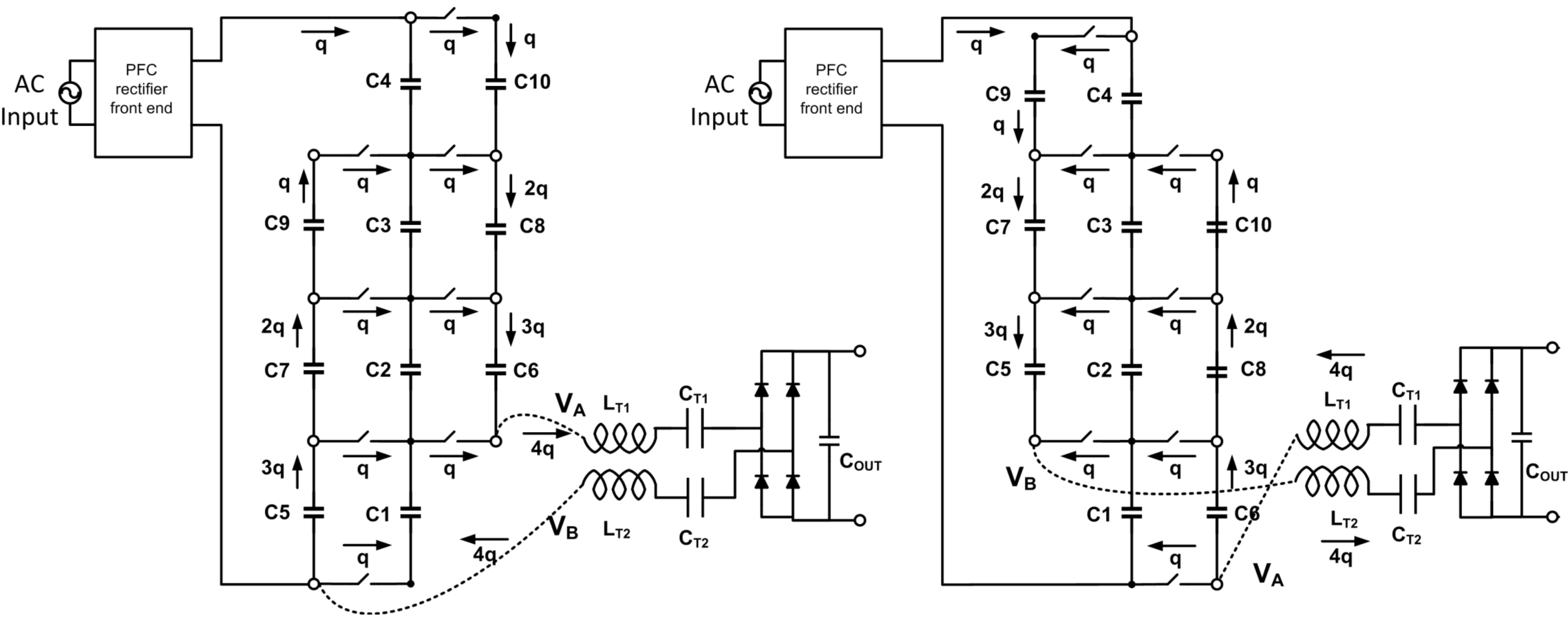
Two Phases of Operation and Output Current Regulation





- Galvanic isolation
- Lossless regulation
- Zero voltage switching

Efficiency Analysis



SSL and FSL charge multiplier vectors:

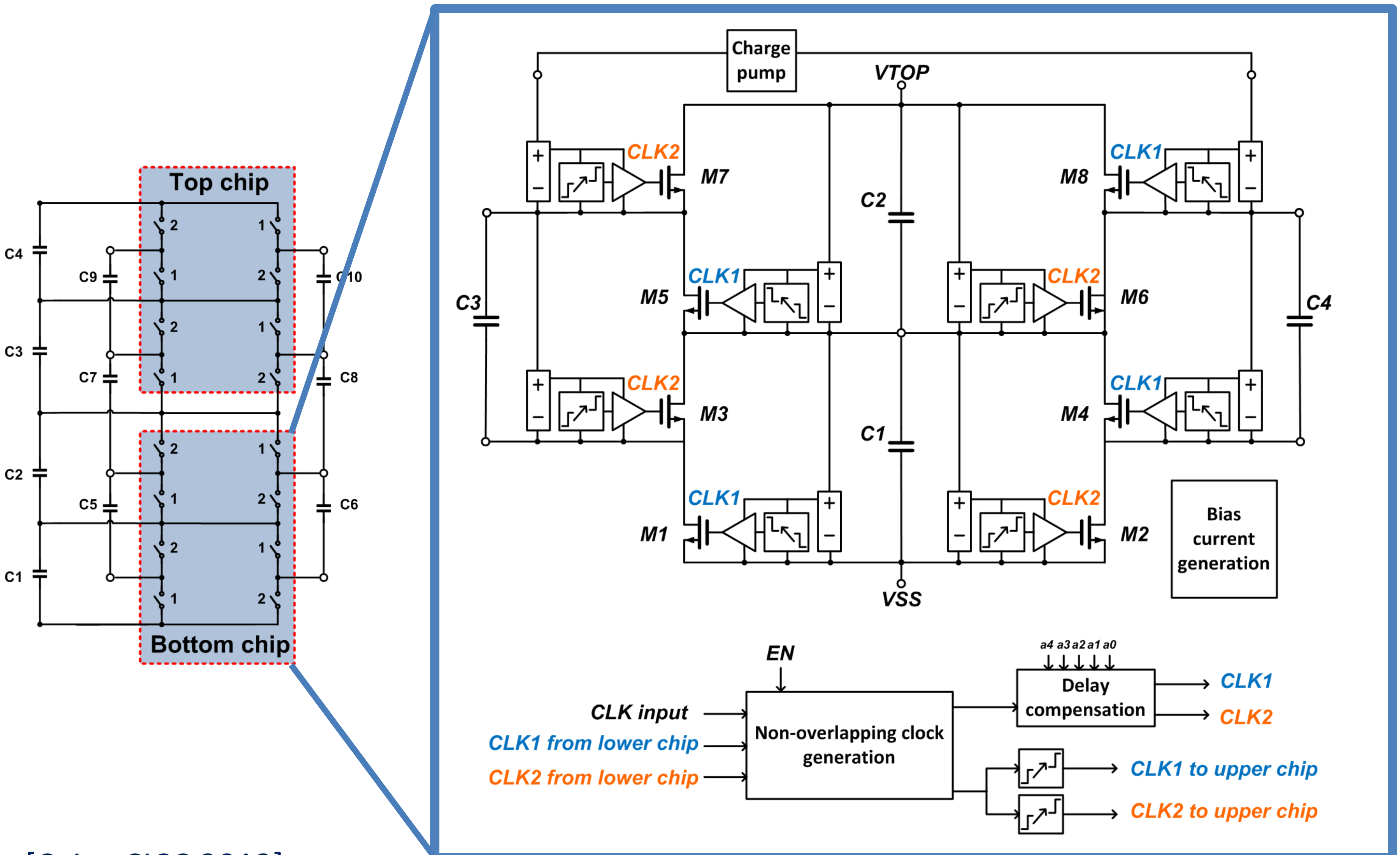
$$a_c = [\frac{3}{8}, \frac{3}{8}, \frac{2}{8}, \frac{2}{8}, \frac{1}{8}, \frac{1}{8}],$$

$$a_r = [\frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}].$$

$$R_{SSL} = \frac{1}{C_{fly} f_{sw}} \sum_{i=1}^{n-1} 2(\frac{i}{2n})^2 = \frac{(n-1)(2n-1)}{12n} \frac{1}{C_{fly} f_{sw}} = \frac{7}{16} \frac{1}{C_{fly} f_{sw}},$$

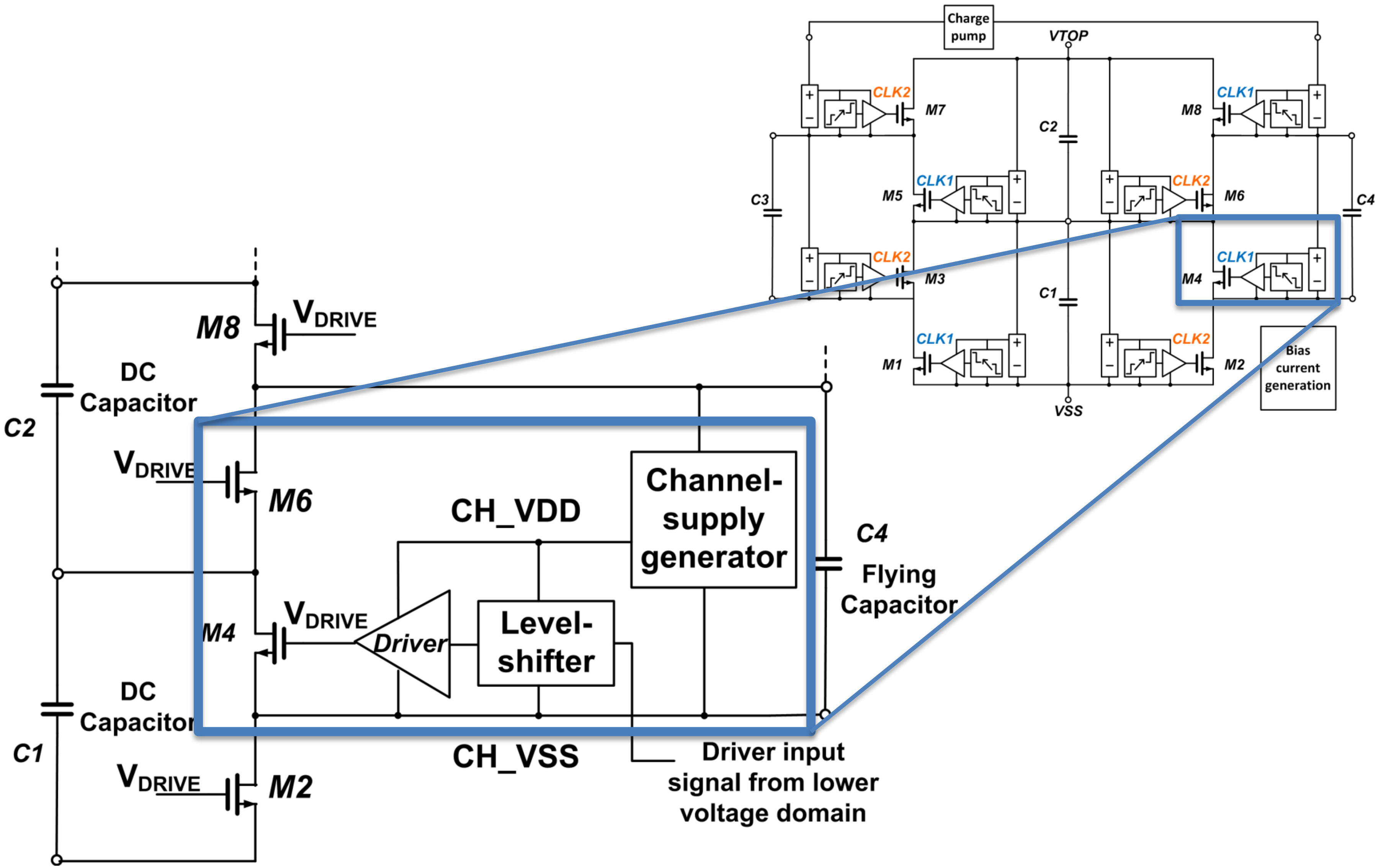
$$R_{FSL} = 2 \sum_{i=1}^{2n} R_i (\frac{1}{2n})^2 = \frac{R_{on}}{n} = \frac{R_{on}}{4},$$

Architecture of the DC-DC Converter IC



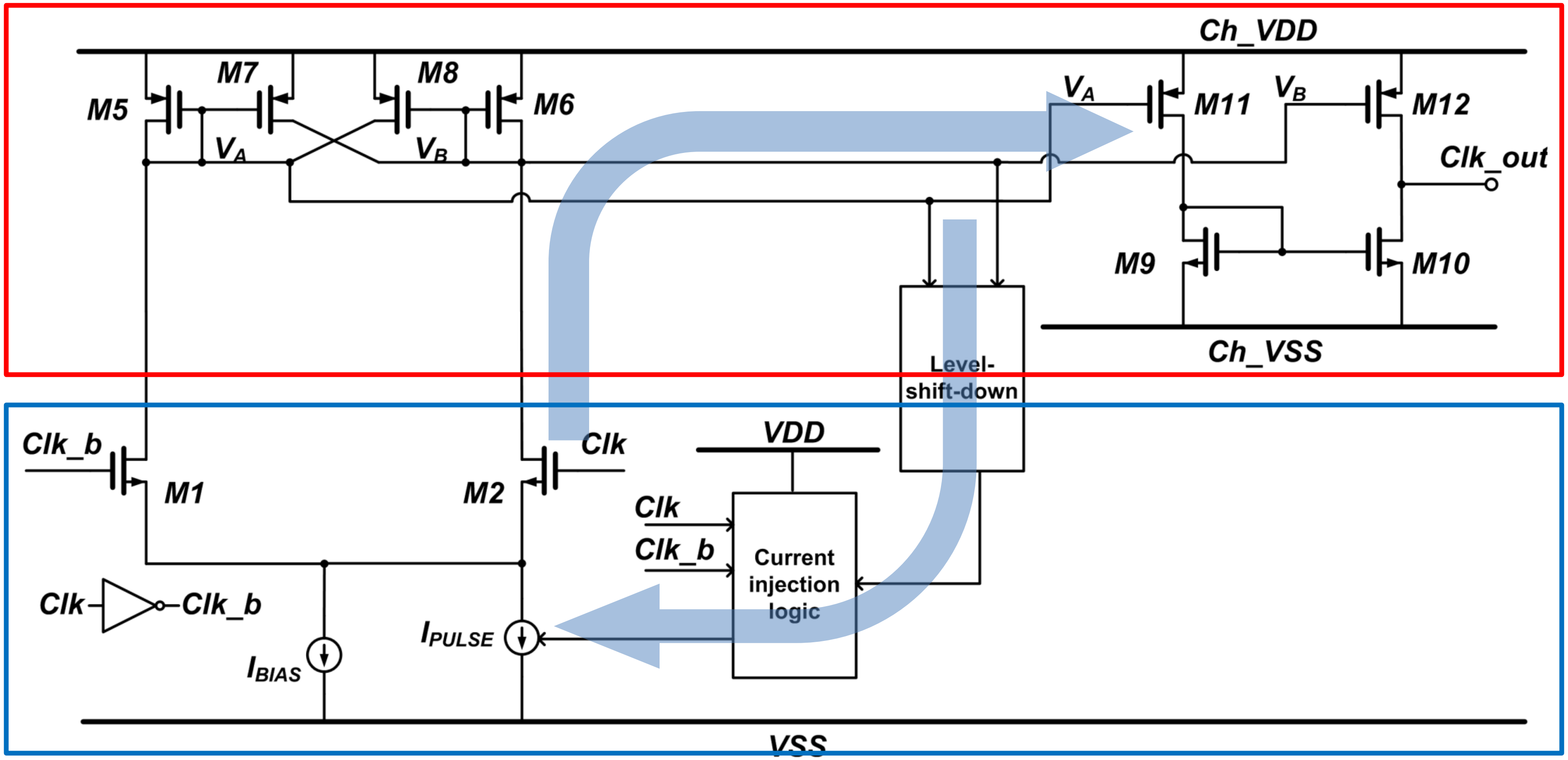
[C. Le, CICC 2013]

Gate-driving Circuits



Level-shifting Circuit

Ch_VDD to Ch_VSS

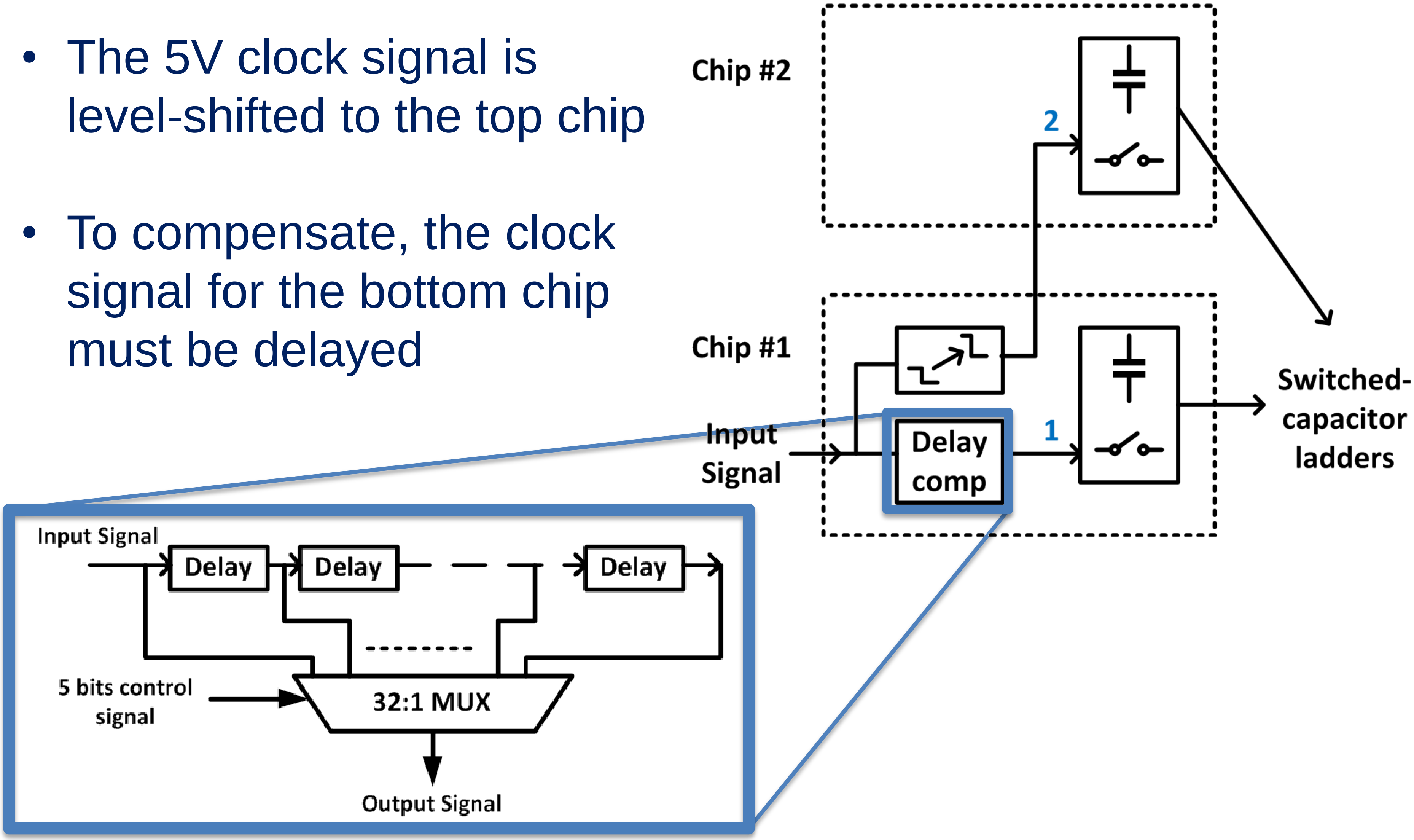


VDD to VSS

Delay Cancellation Strategy

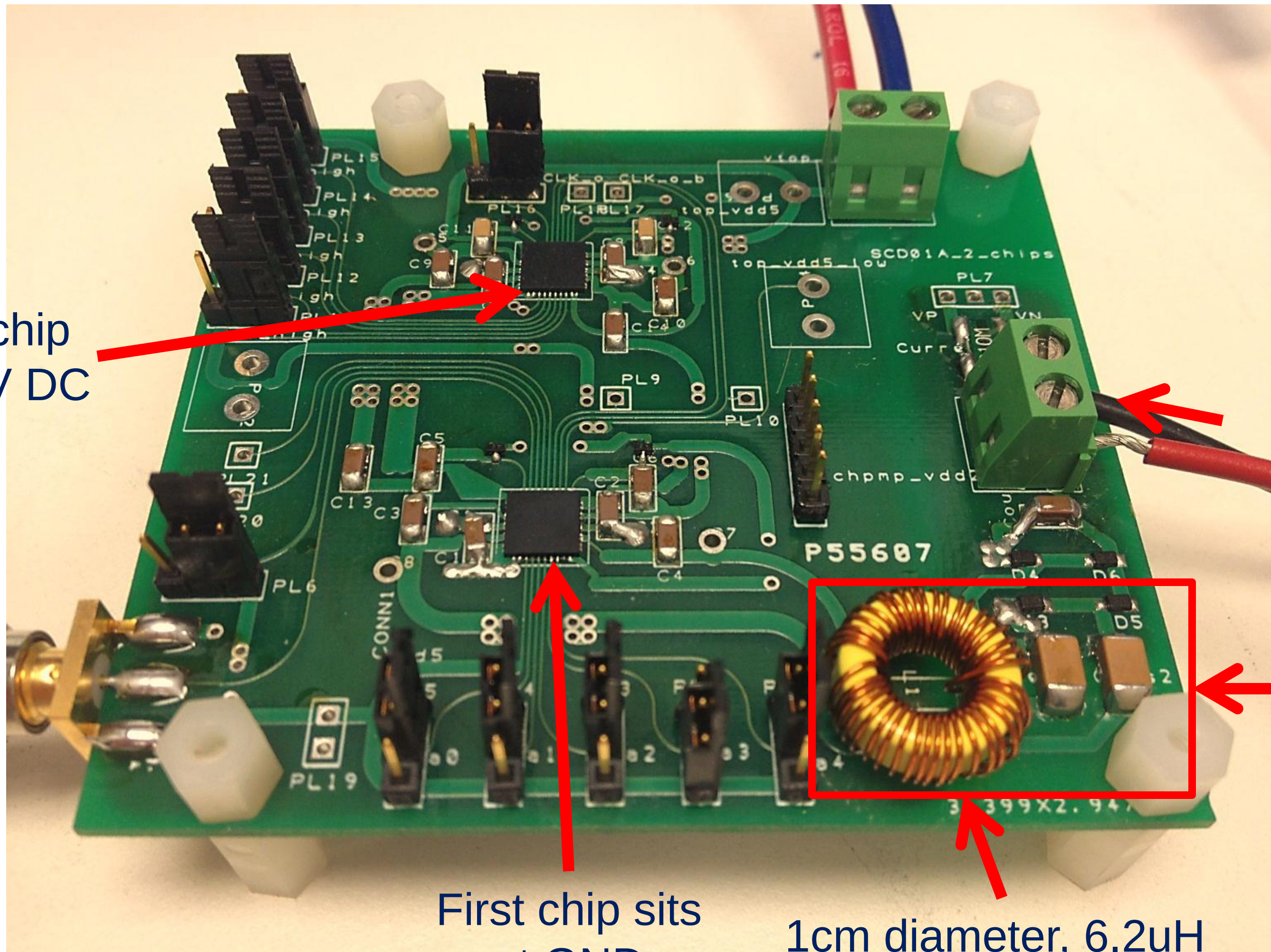
- The 5V clock signal is level-shifted to the top chip

- To compensate, the clock signal for the bottom chip must be delayed



Test Board for a 170V Input 17W LED Driver

DC input up to 200V



Second chip sits at 85V DC

DC output to the LEDs

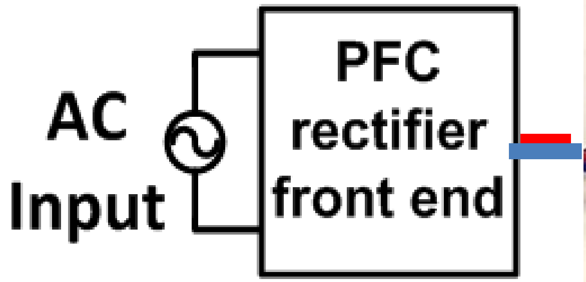
Clock input

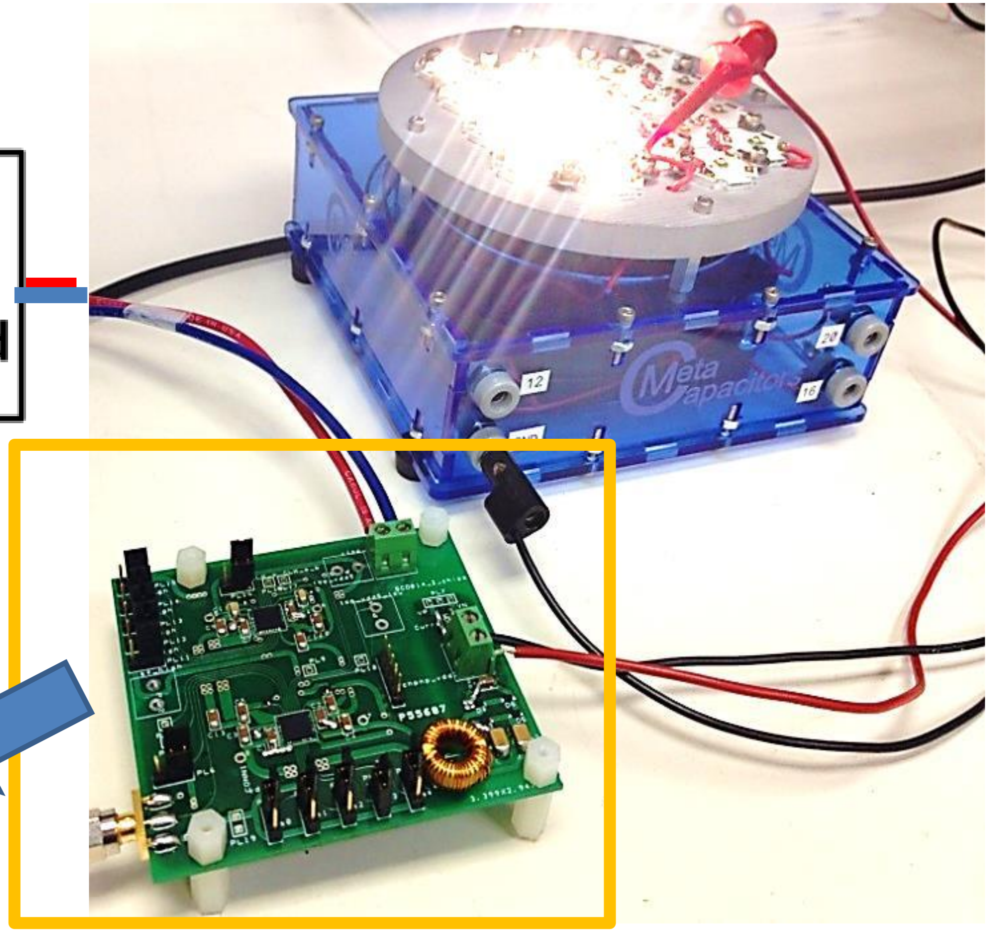
Capacitive power transfer & galvanic isolation, 3kV rated

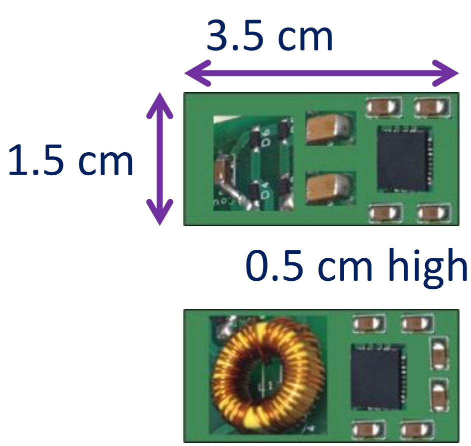
First chip sits at GND

1cm diameter, 6.2uH Split winding inductors

Possible Compact Layout of PCBs

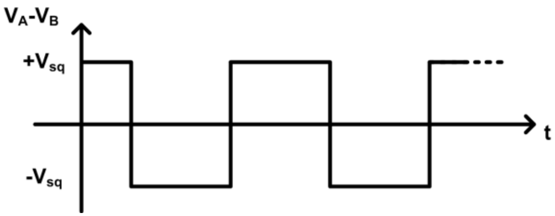


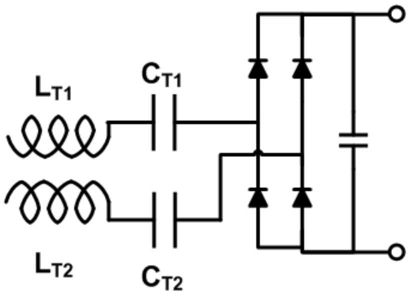


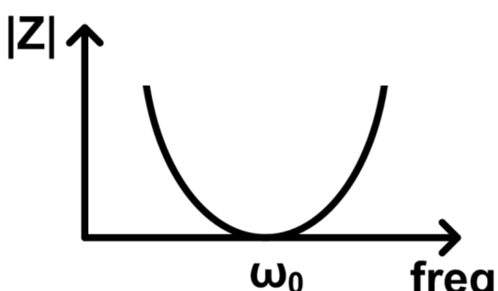


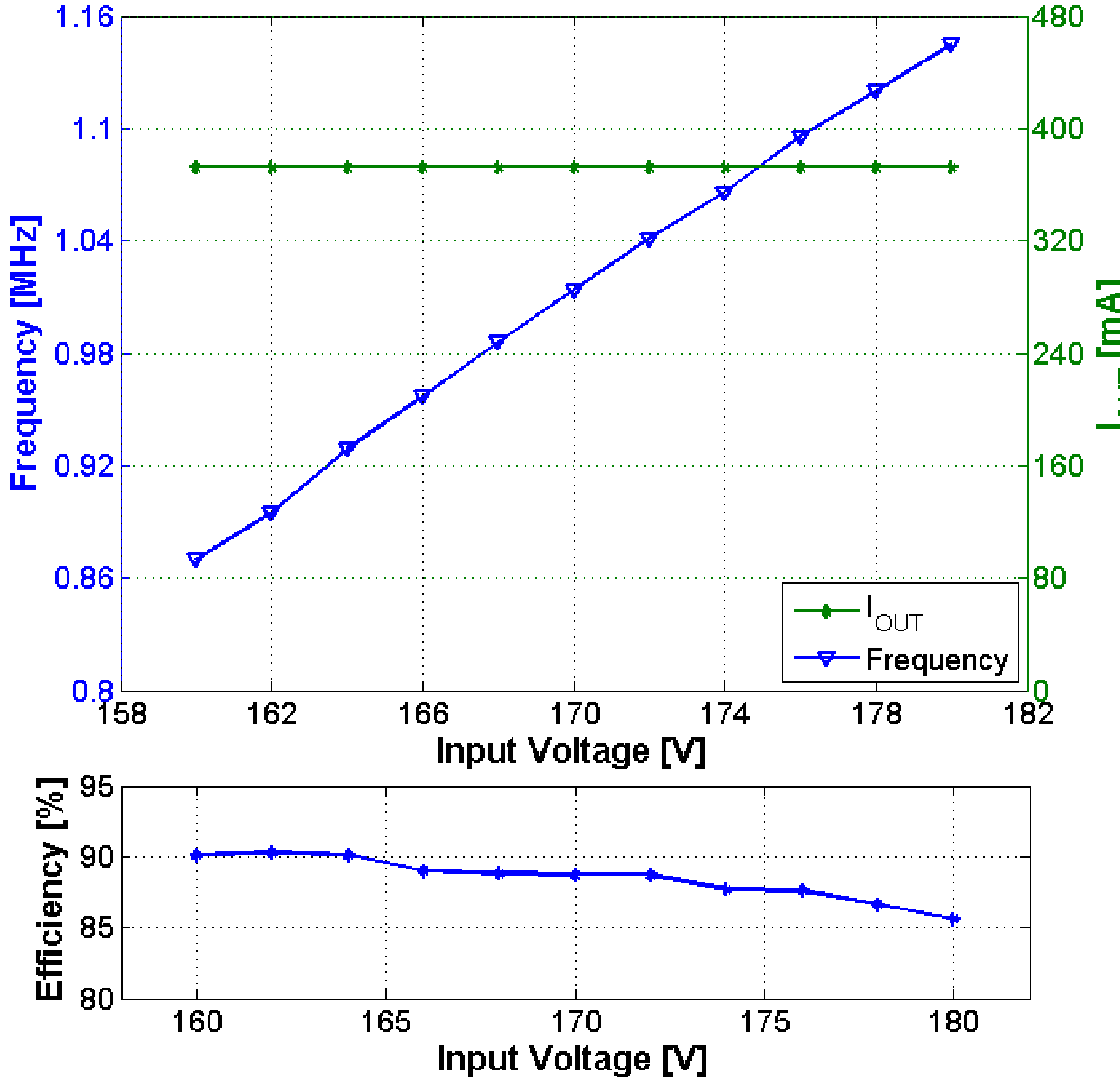
137.5 W/inch^3

Current Regulation versus V_{in}

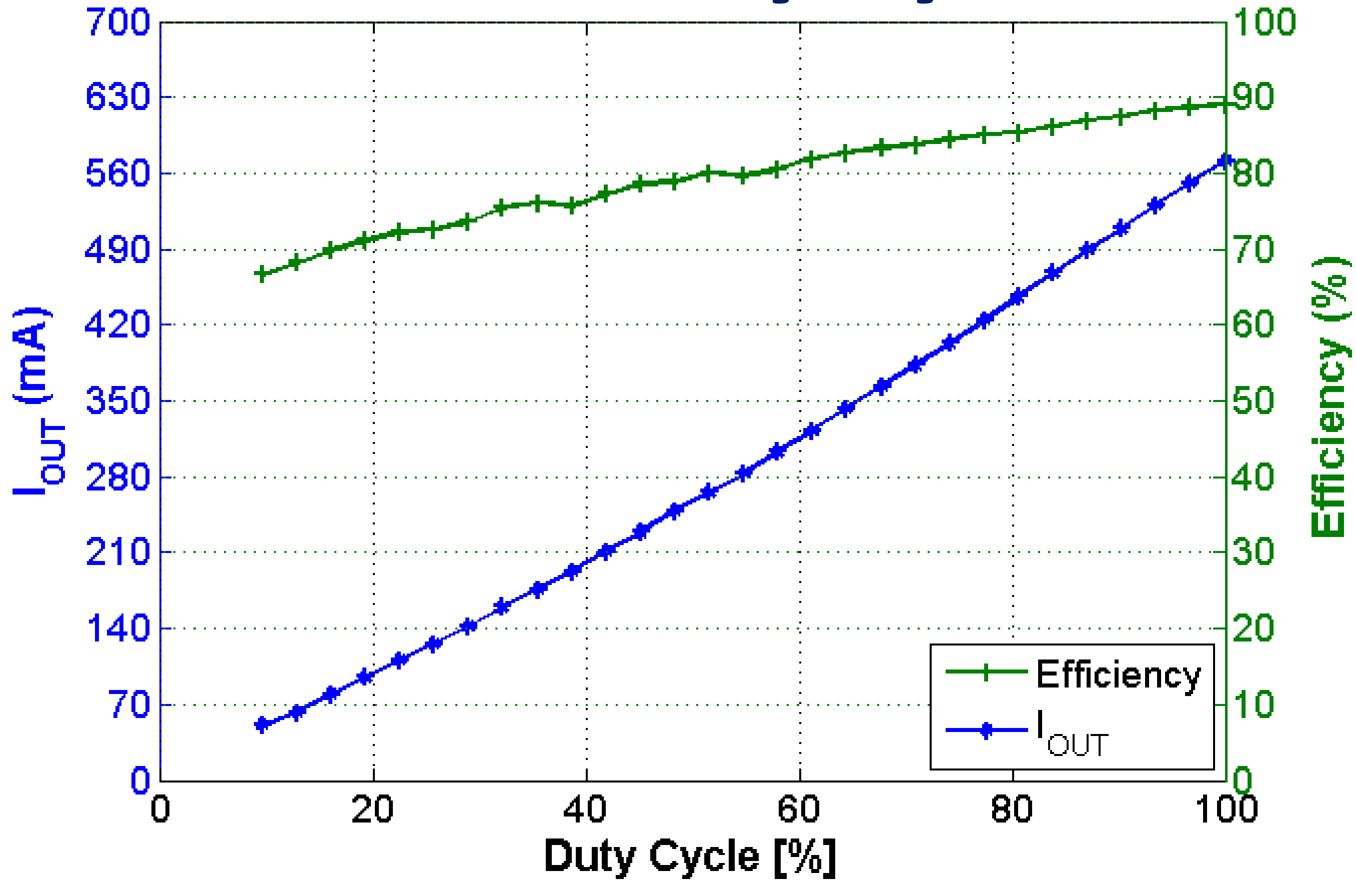




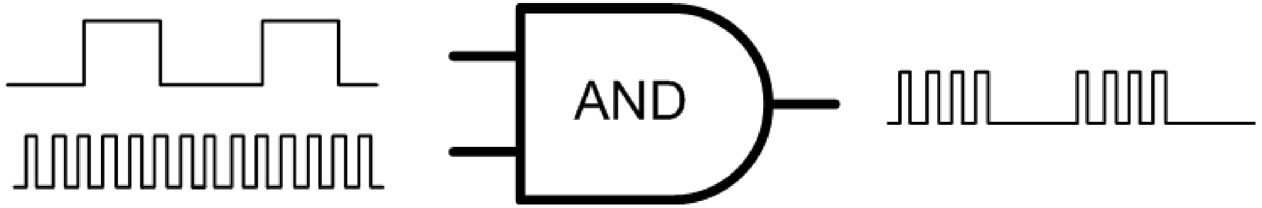




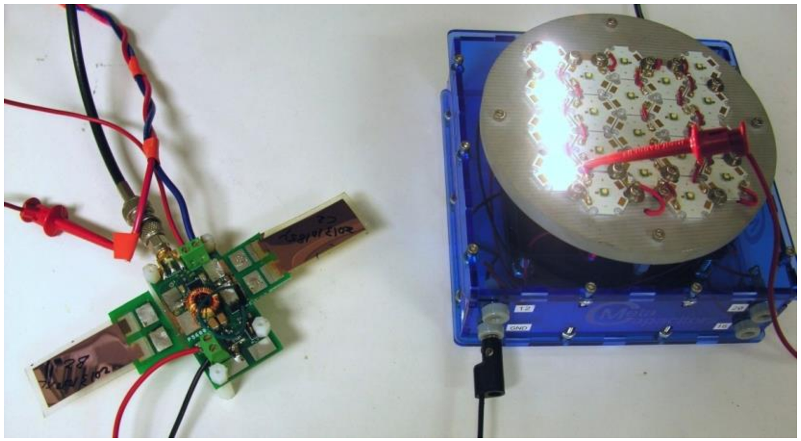
Current Regulation and Efficiency versus Duty Cycle

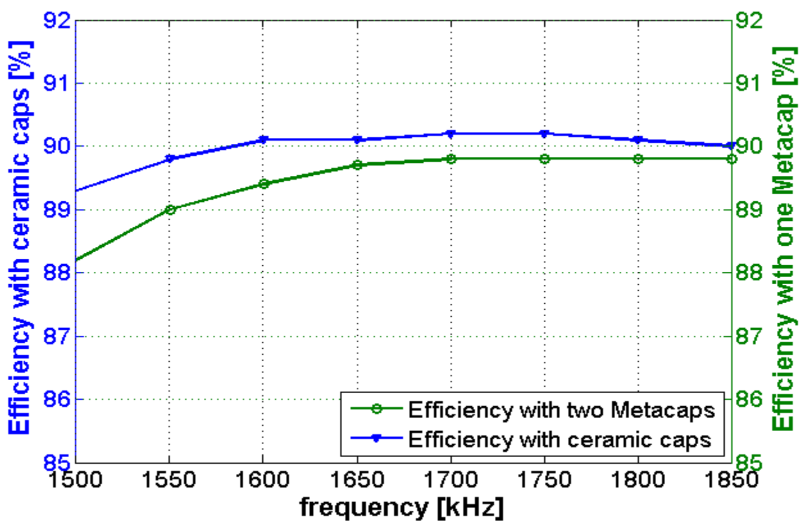


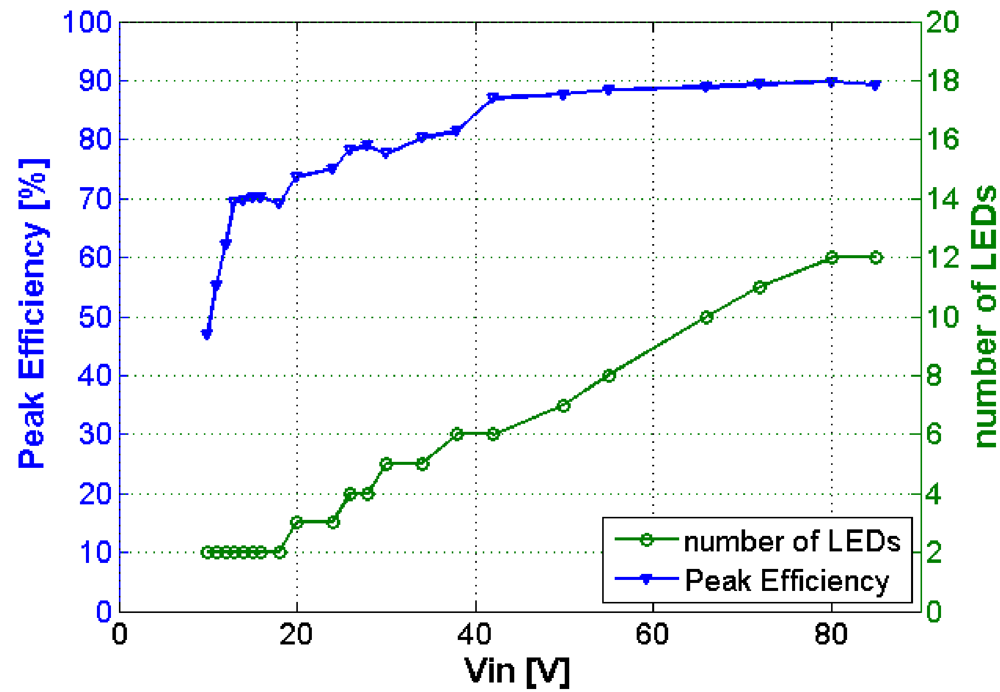
PMW clock dimming control



First Integration with Metacapacitors







- ESR of the connector and the printed thin film could be a problem
- The capacitance of the printed Metacap is slightly smaller

Summary

- Presents a chip-stackable Switched-Capacitor (SC) DC-DC converter IC for a **hybrid-SC-resonant (HSCR) LED driver**.
- Combines the advantages of **high energy density capacitors**, the **SC converter** and the **series-resonant converter**, achieving an optimized use of reactive elements.
- Developed a **Chip-stackable integrated SC module**. The converter can be reconfigured and extended to handle different input voltage levels with relatively constant efficiency.
- The HSCR converter offers near lossless regulation, galvanic isolation and dimming function with small size reactive components.
- One of the highest power SC converters compared to the current state of the art .

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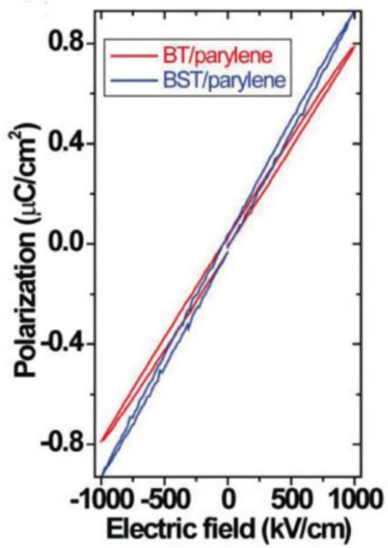
Thank you!

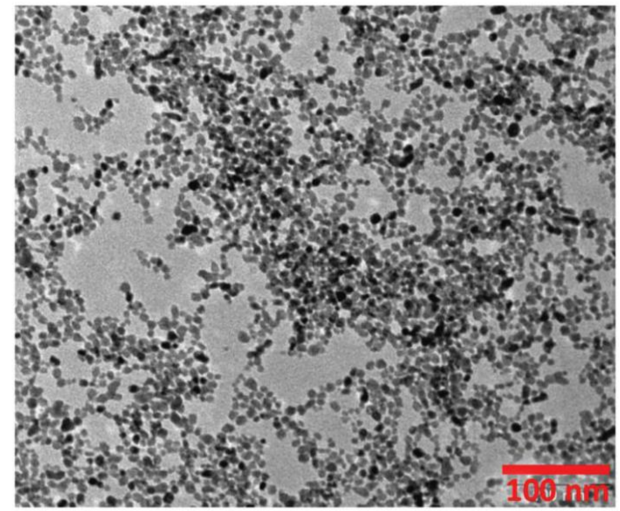
Questions?

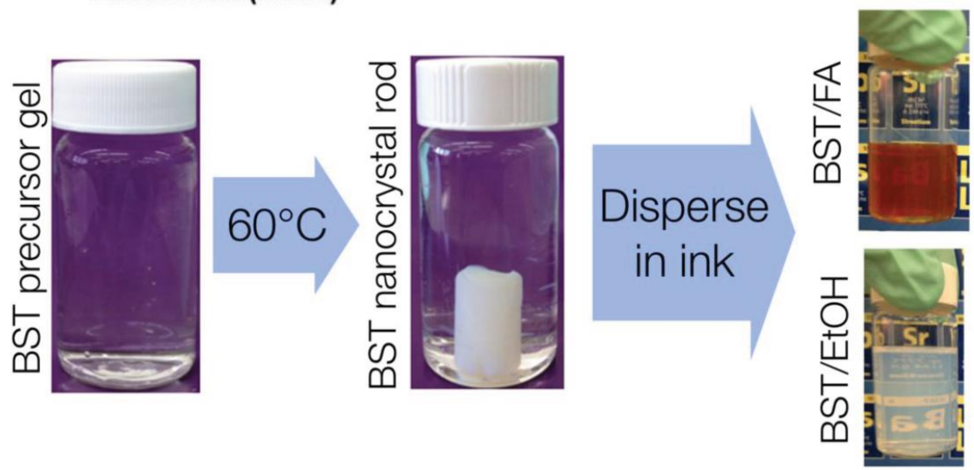
Metacapacitors™

Printable nanoparticle dielectric for high frequency capacitors

- High frequency performance with low loss–single crystal nanoparticles exhibit no ferroelectric hysteresis
- Nanoparticle dielectric inks are readily printable and are compatible with spin coat deposition
- Synthesized below 100°C, No HTCC/LTCC required
- $BaTiO_3$ and (Ba, Sr)TiO_3 nanoparticles, size controllable from 5-100 nm
- No rare earth materials





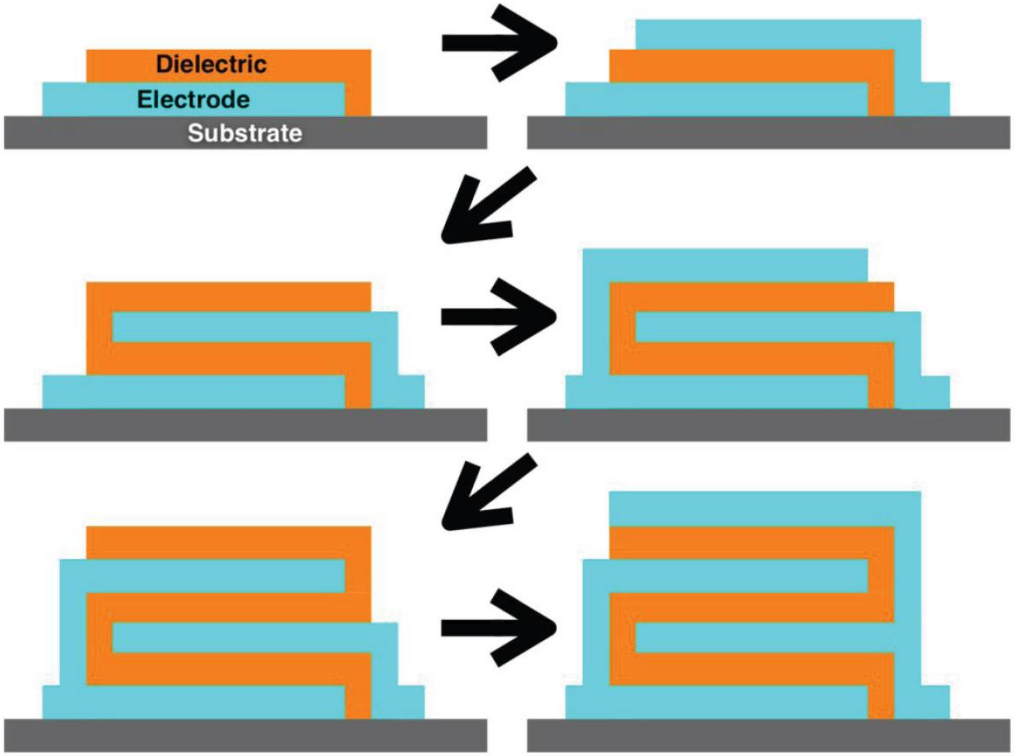


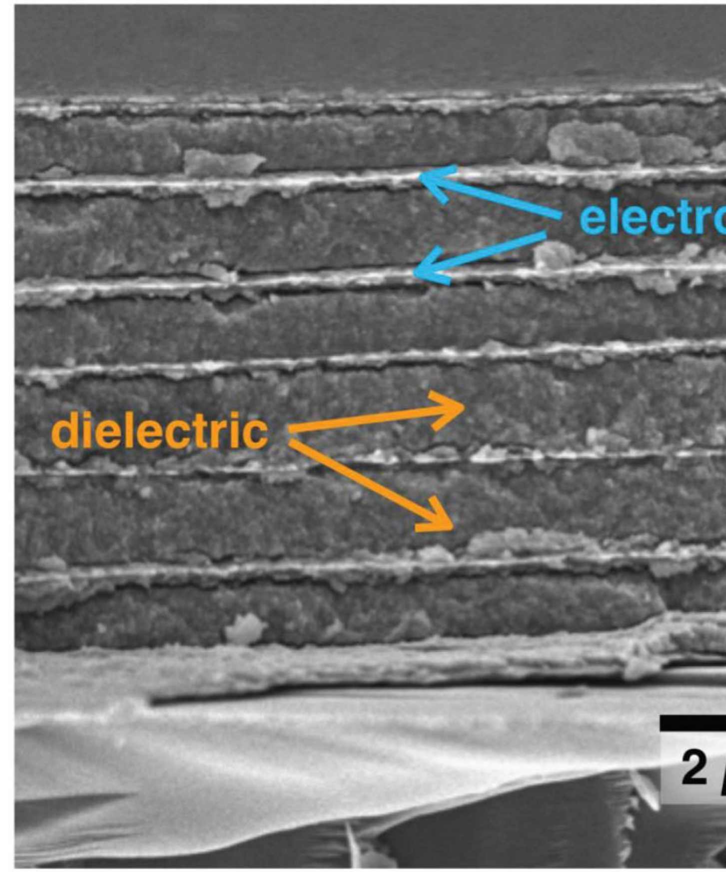
O'Brien, S., Huang, L. & Chen, Z. METAL OXIDE NANOCRYSTALS: PREPARATION AND USES. USA patent application 12/566,135

CUNY ENERGY INSTITUTE

Metacapacitors™

Printed multilayer capacitors for power conversion





- Purely additive, roll-to-roll compatible spray-coat or gravure depos
- All processing below 200 °C

Metacapacitors™

Printed multilayer capacitors high-frequency performance

Wide-area spray-printed multilayer capacitor