Energy Harvesting Circuit & Chip

Course project of *Analog Integrated Circuit Design*

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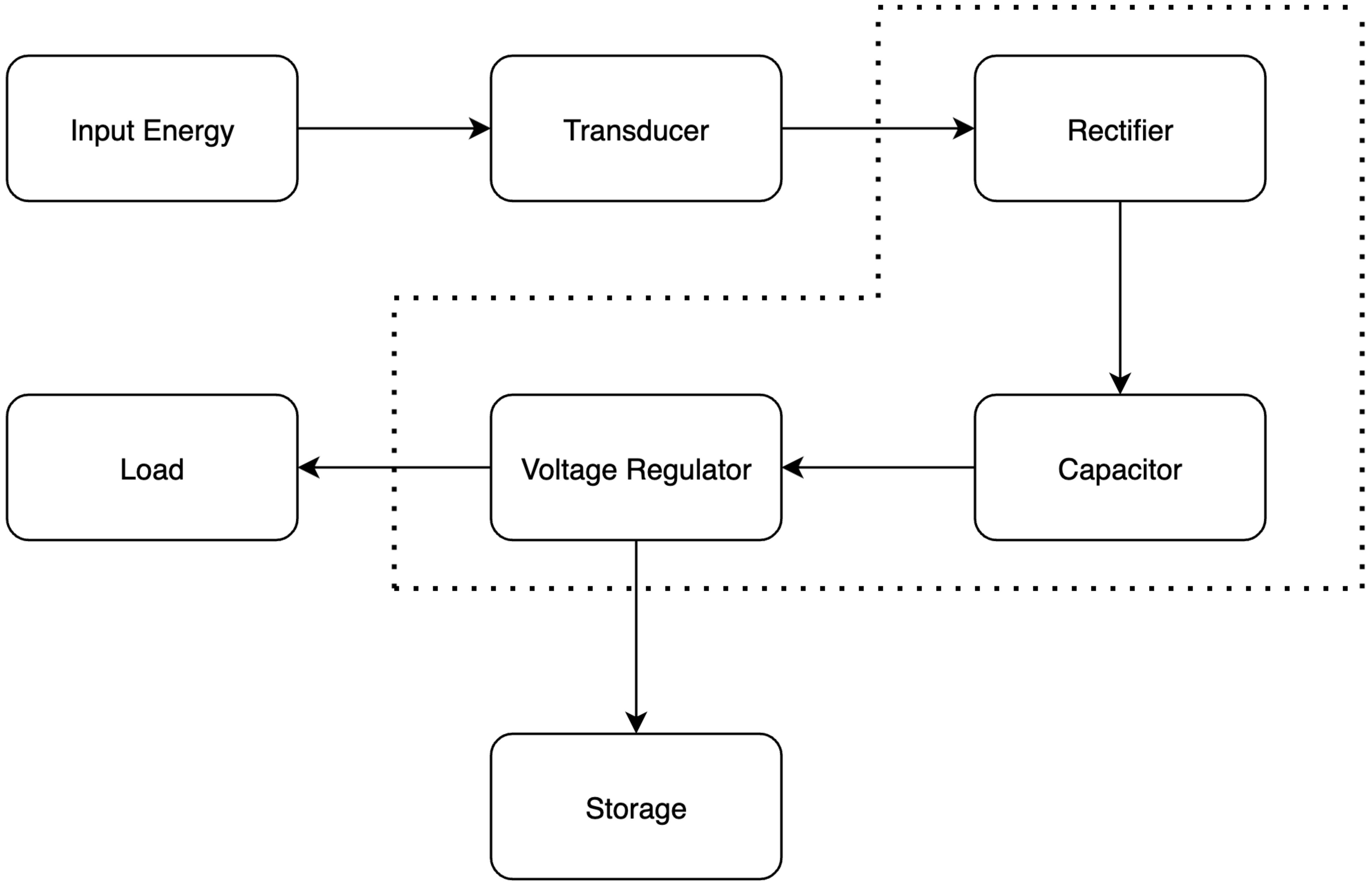
Contents

Energy harvesting system

- Main components
  - Transducer
  - Power management system
  - Load & storage



Transducer

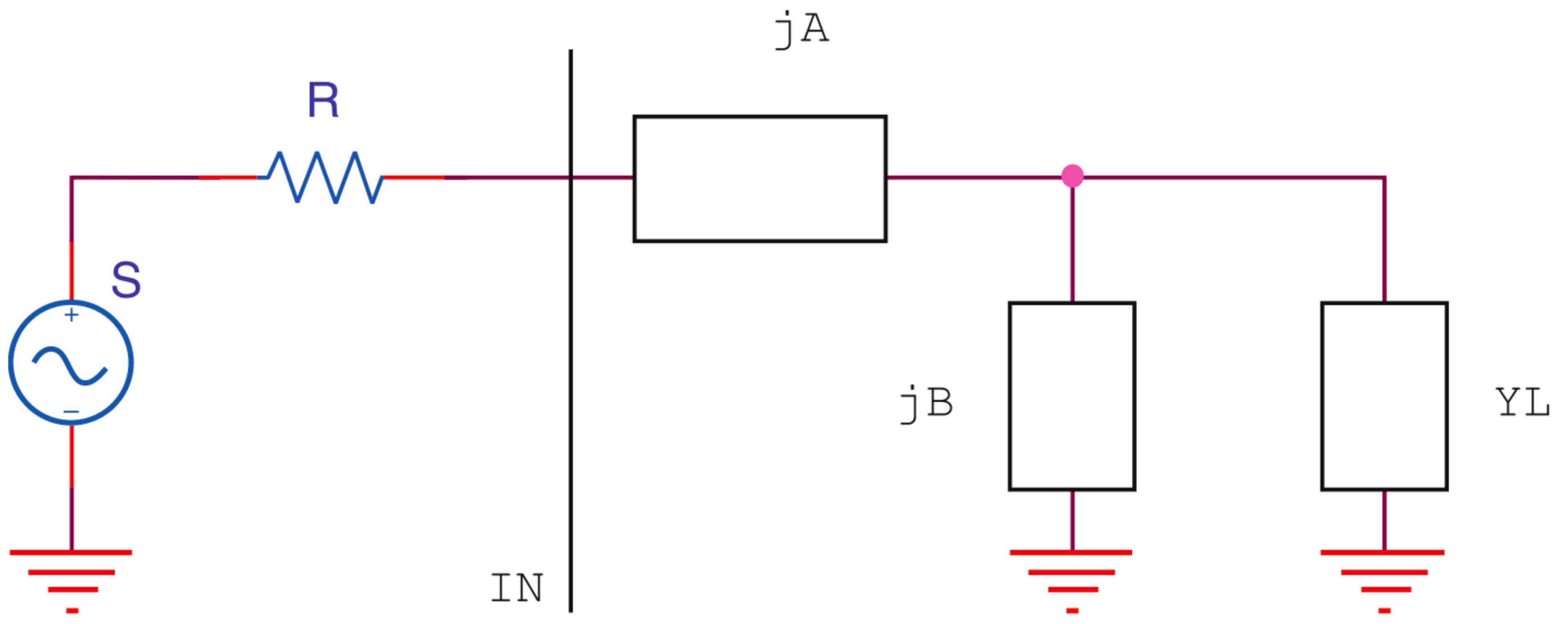
- Convert ambient energy into electrical energy of input
- Ambient energy types
  - RF signal — electromagnetic transducer
  - Vibration — piezoelectric transducer
  - Heat — thermoelectric modules
  - Light — photovoltaic cells
  - …

Electromagnetic transducer

- Receiving antenna pick up radio waves from transmitting antenna
- Friis transmission formula [1]

$$\frac{P_r}{P_t} = D_t D_r (\frac{\lambda}{4\pi d})^2$$

- Matching network [2]



Electromagnetic transducer

- Output voltage [2]

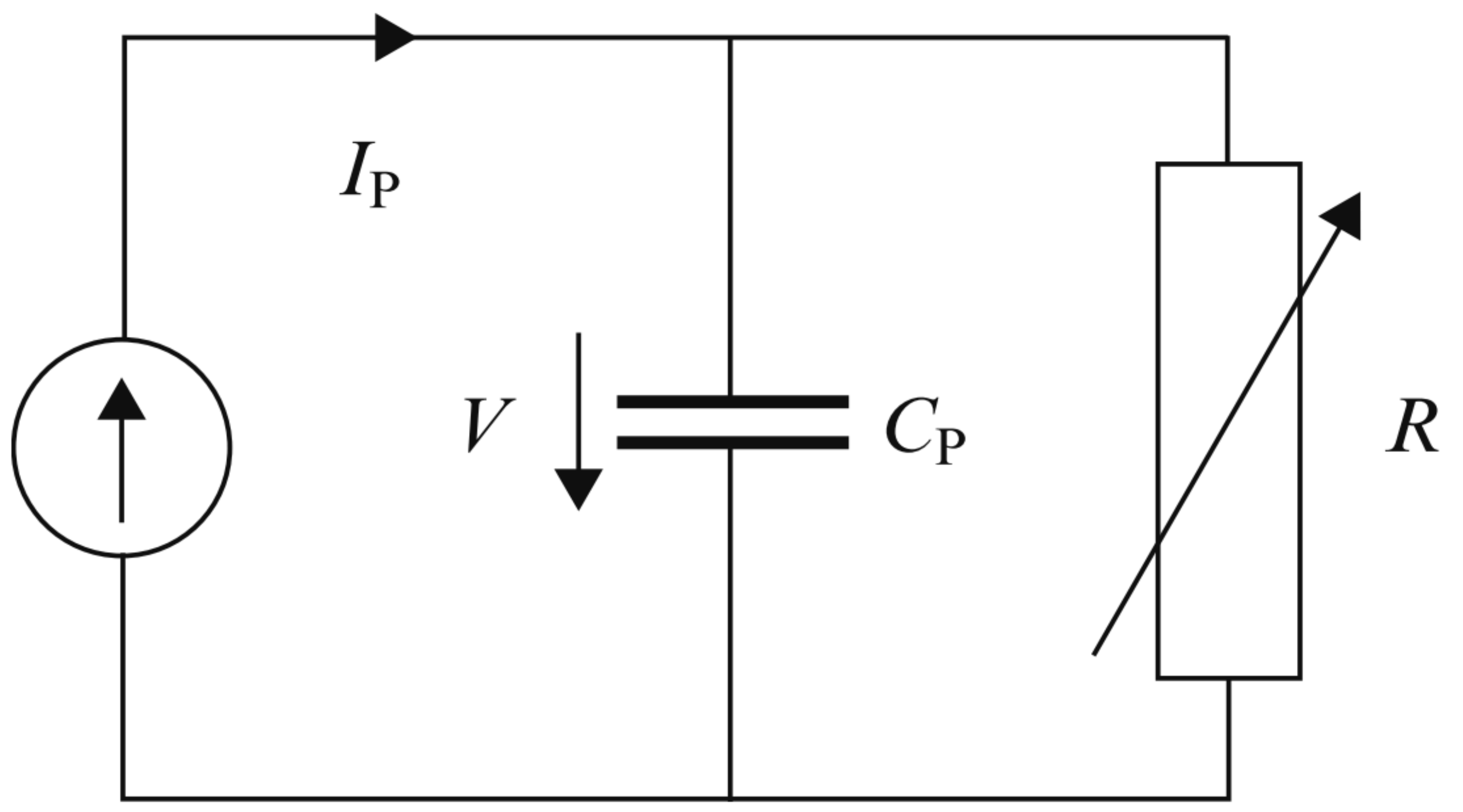
$$v_{out} = \frac{1}{2}\sqrt{1 + Q^2} \times 8R^2 P_{inc}$$

- Existing RF energy harvesting system in Europe [2]

System	Downlink (MHz)
GSM900	935~960
GSM1800	1805.2–1879.8
WiFi	2400 ~ 2500

Piezoelectric transducer

- Piezoelectric transducer accumulates electric charge in response to applied mechanical stress [3]
- Piezoelectric materials: quartz, langasite, gallium orthophosphate
- Equivalent circuit of piezoelectric element



Piezoelectric transducer

- Add sinusoidal excitation

$$I_p(t) = Isin(\omega t)$$

- Maximum output power

$$P_{max} = \frac{I^2}{2\omega C_p}$$

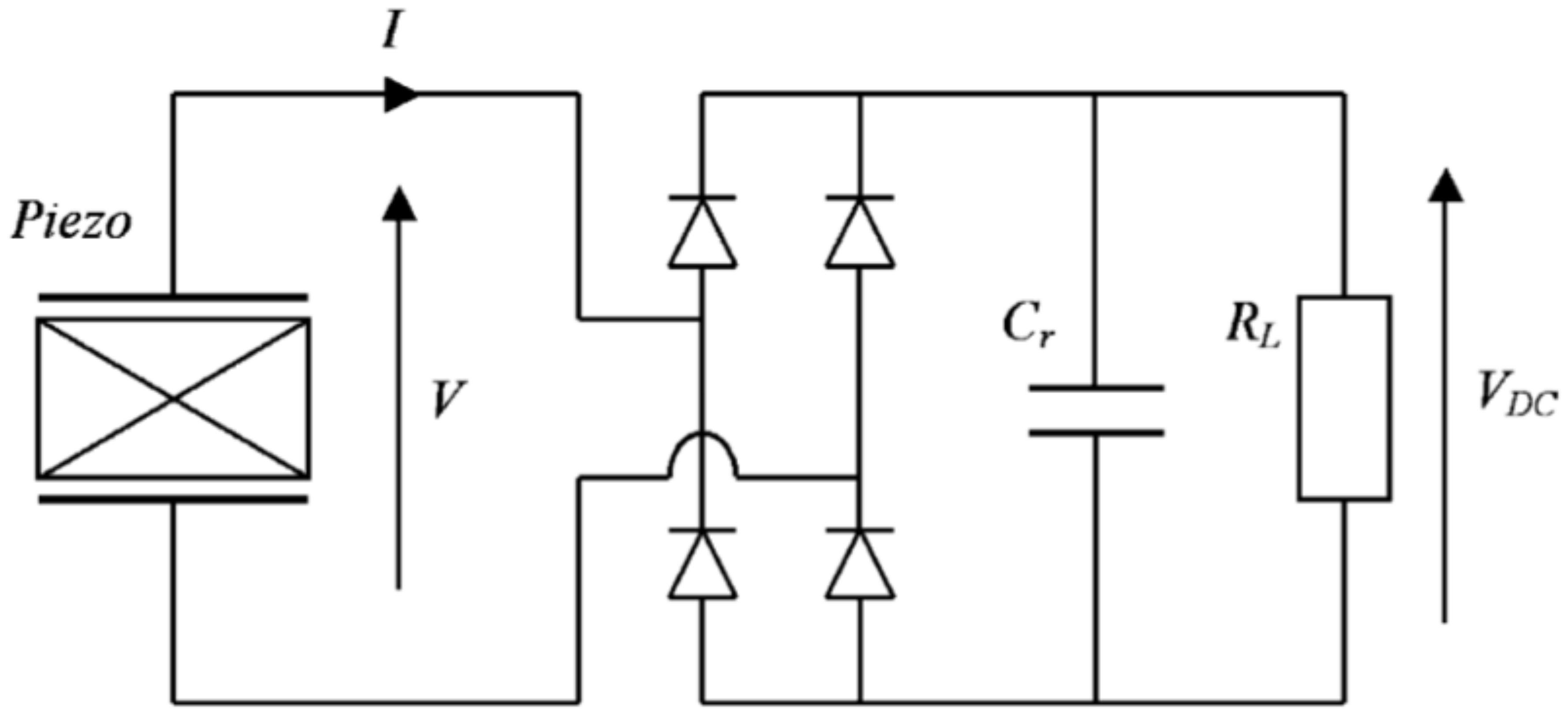
- Electromechanical coupling coefficient
  - Conversion efficiency between electrical and acoustic energy
  - Determines the choice of interface circuit

Key parameters

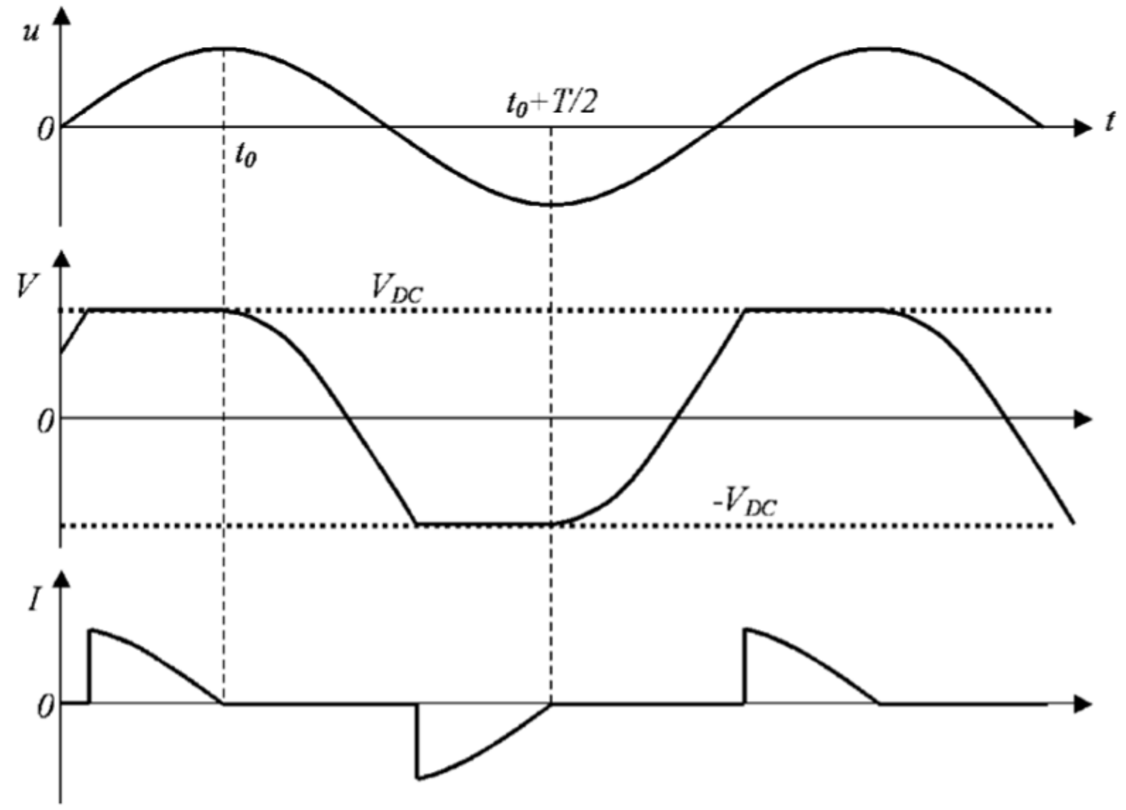
- Harvested power independency
- Power gain
- Operation independency
- Autonomy
- Self-powering/high efficiency
- Startup

Standard interface

- Simplest interface circuit
- Consists of diode-bridge rectifier with parallel RC shunt filter
- Works under weak coupling condition



Standard interface



Steady state signal

Standard interface

- Stay state output

$$V_{DC} = \frac{R_L \alpha}{R_L C_0 \omega + \frac{\pi}{2}} \omega U_M$$

$$P = \frac{R_L \alpha^2}{(R_L C_0 \omega + \frac{\pi}{2})^2} \omega U_M$$

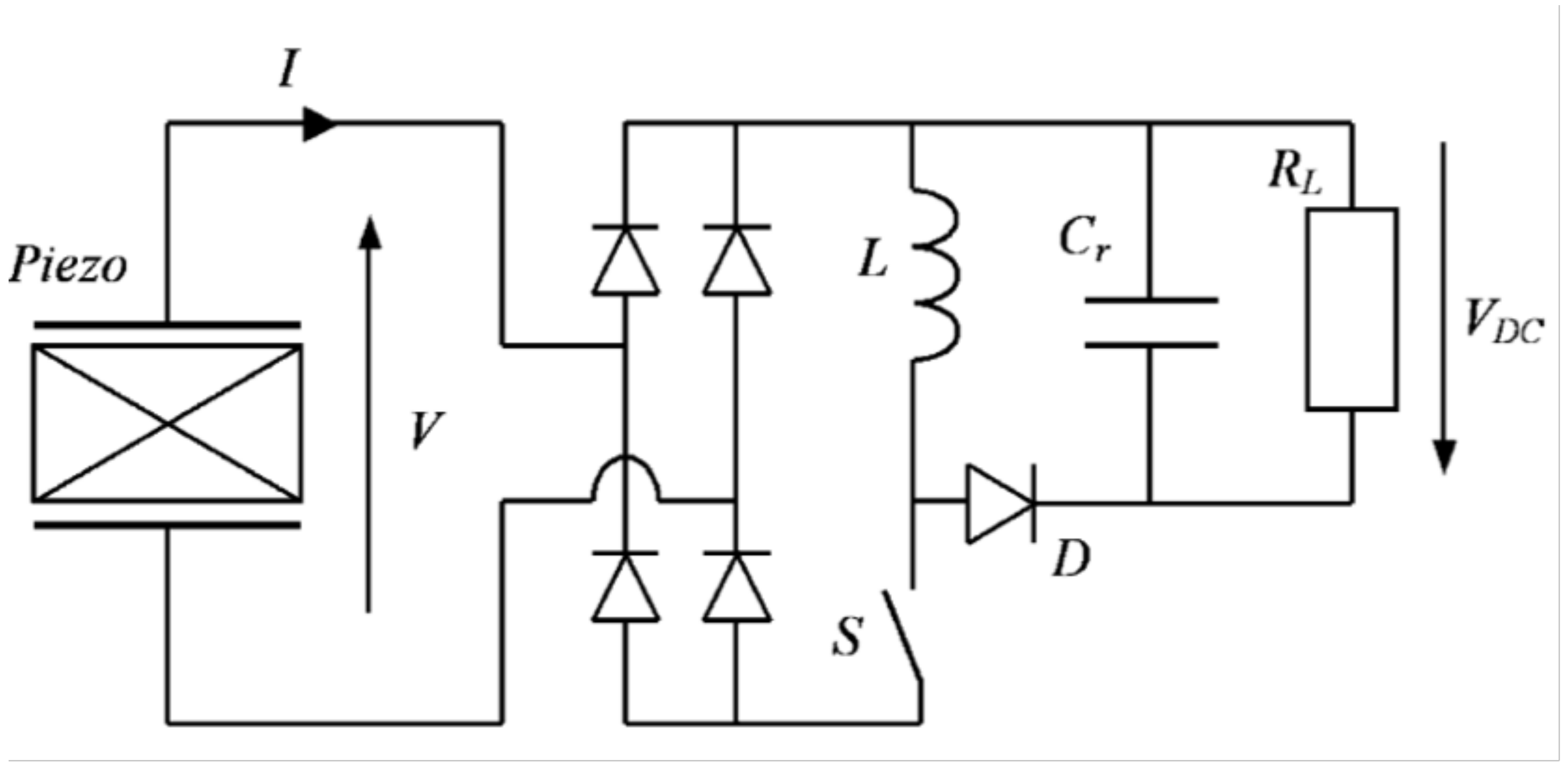
- Max power output

$$P_{max} = \frac{\alpha^2 \omega}{2\pi C_0} U_M^2$$

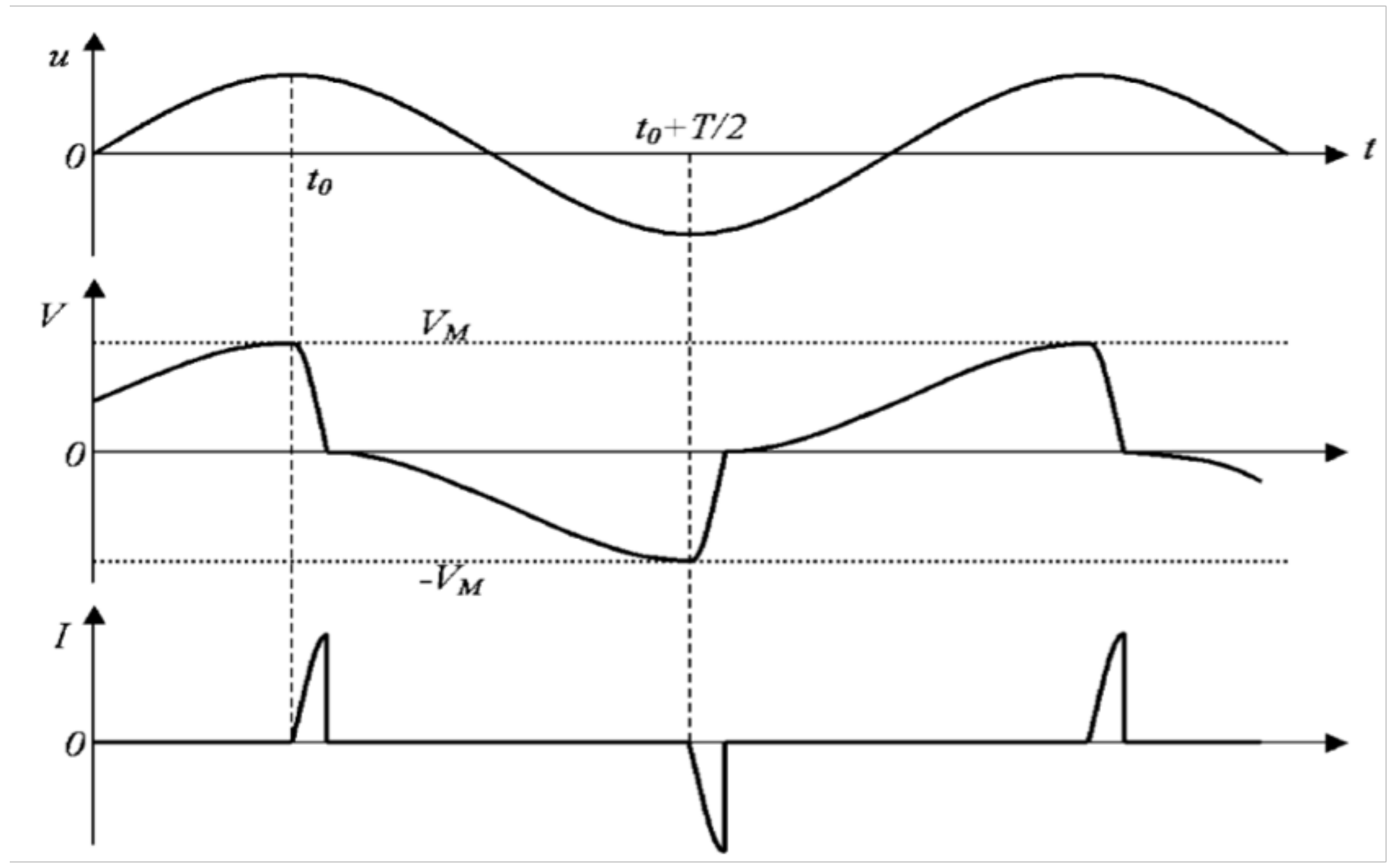
$$R_{opt} = \frac{\pi}{2 C_0 \omega}$$

SECE interface

- SECE: Synchronous electric charge extraction
- Periodically remove the charge on blocking capacitor
- Small power wasted in non-charge transfer phase



SECE interface



Steady state signal

SECE interface

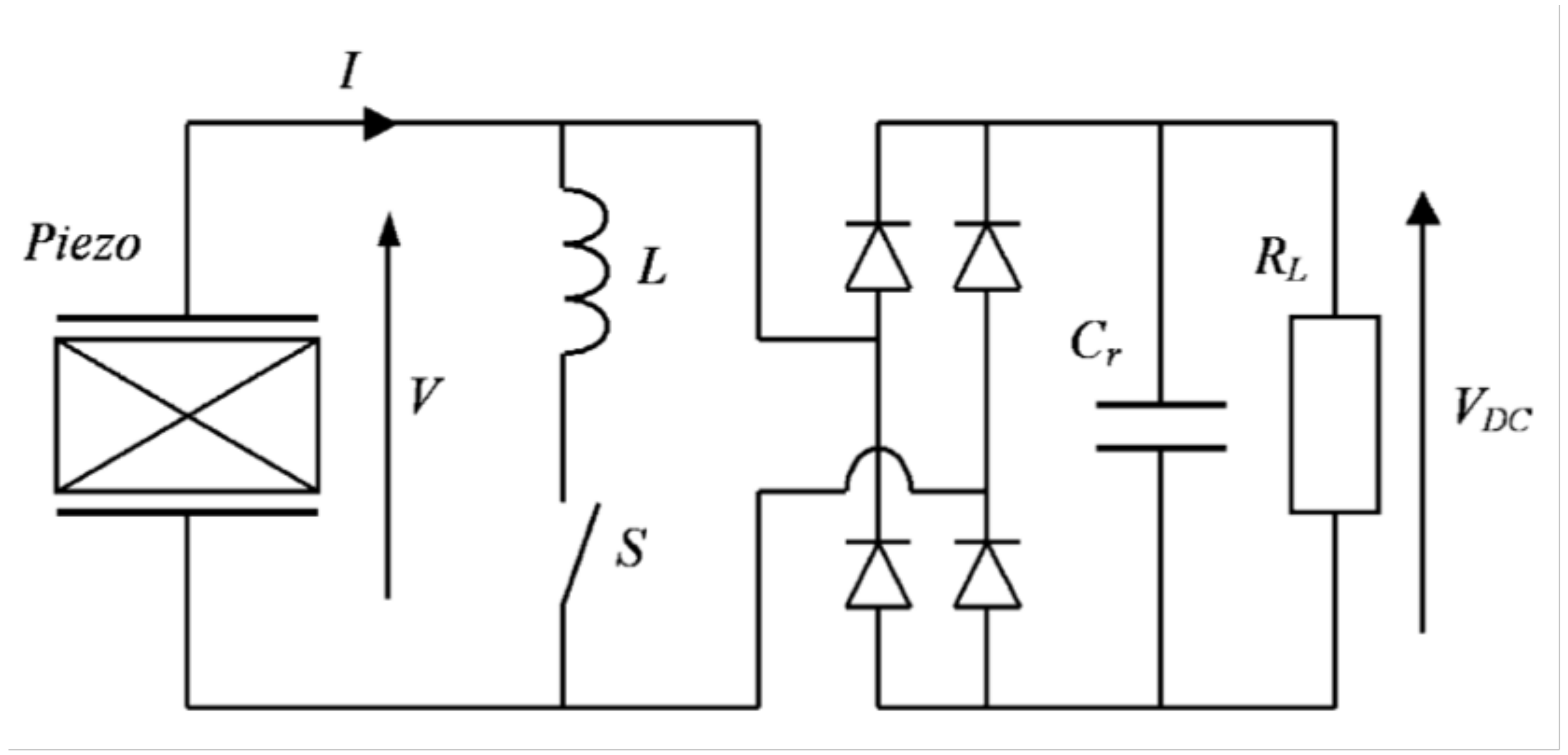
- Steady state output

$$V_m = 2\frac{\alpha}{C_0}U_M$$

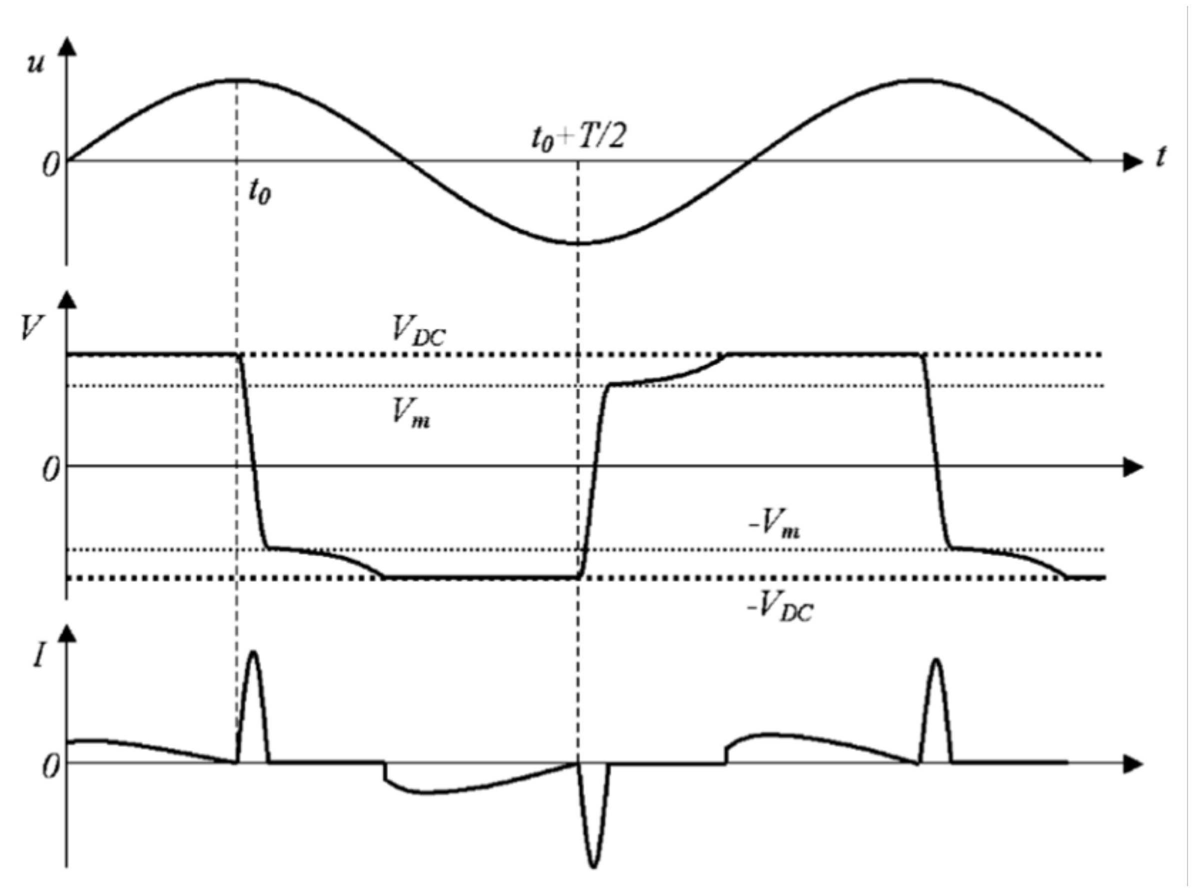
$$P = 2\frac{\alpha^2\omega}{\pi C_0}U_M^2$$

Parallel SSHI interface

- SSHI: synchronized switch harvesting on inductor
- Parallel non-linear circuit composed of inductor and switch
- Quick reverse of voltage across piezoelectric element



Parallel SSHI interface



Steady state signal

Parallel SSHI interface

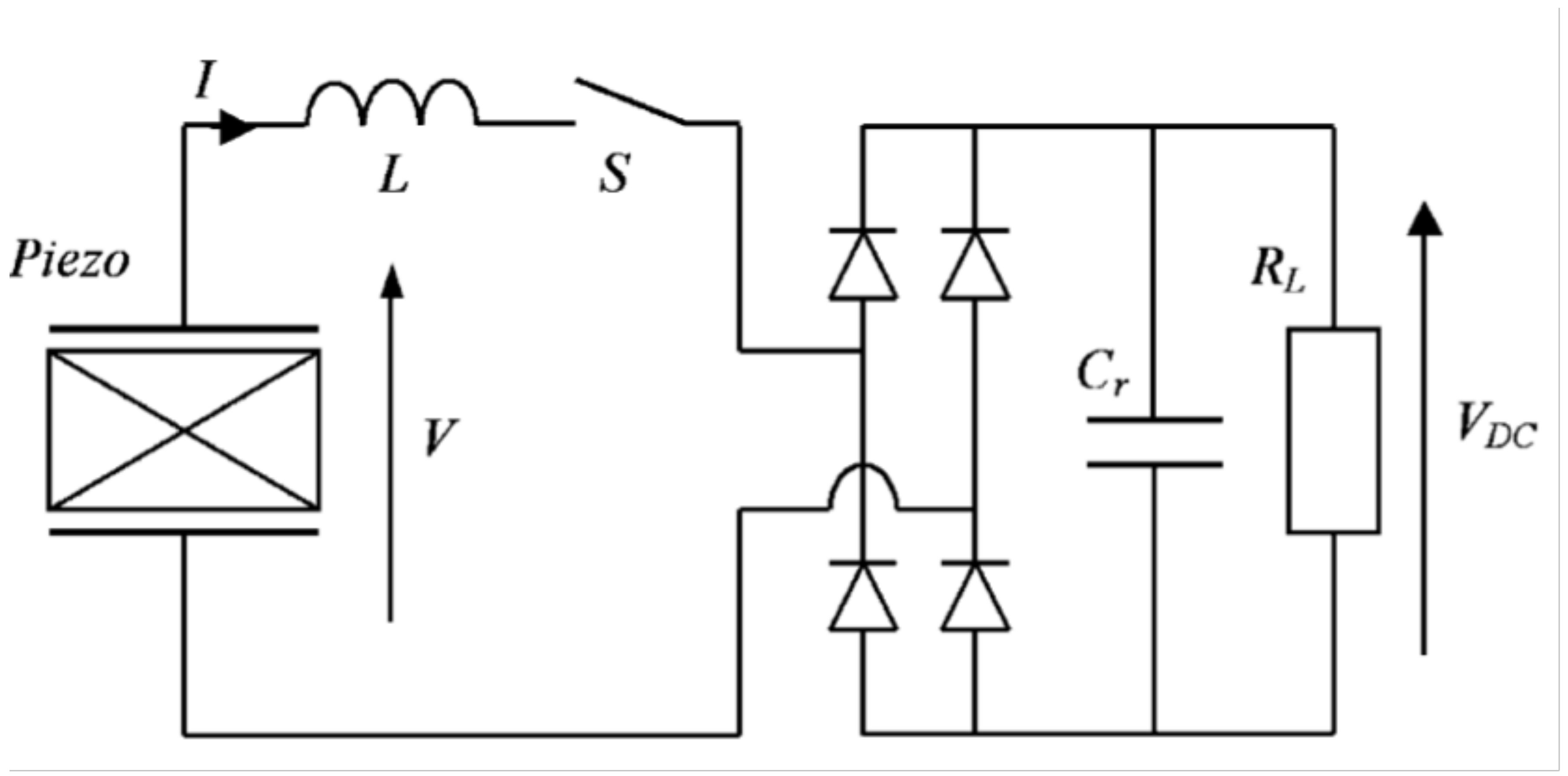
- Max power output

$$P_{max} = \frac{\alpha^2 \omega U_M^2}{\pi C_0 (1 - e^{-\frac{\pi}{2Q_i}})}$$

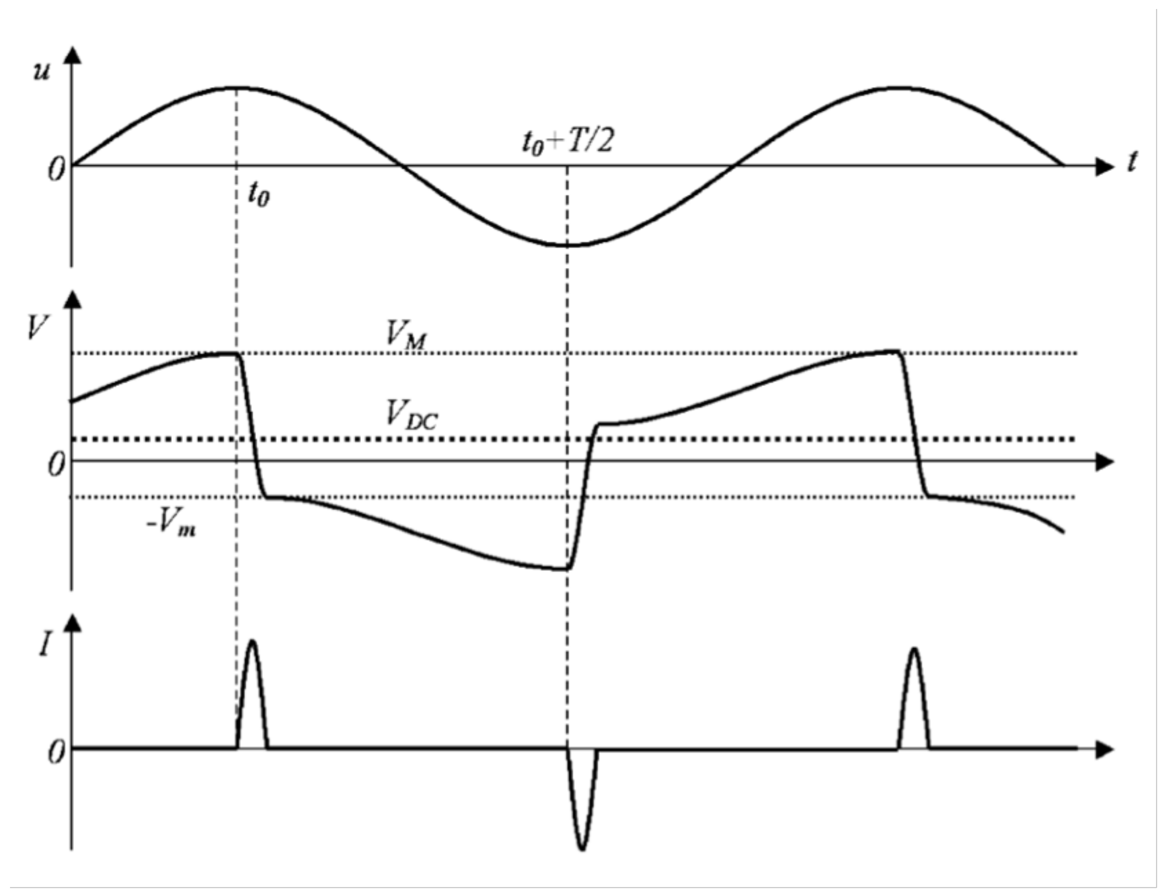
$$R_{opt} = \frac{\pi}{\omega C_0 (1 - e^{-\frac{\pi}{2Q_i}})}$$

Series SSHI interface

- Series non-linear circuit composed of inductor and switch
- Quick reverse of voltage across piezoelectric element



Series SSHI interface



Steady state signal

Series SSHI interface

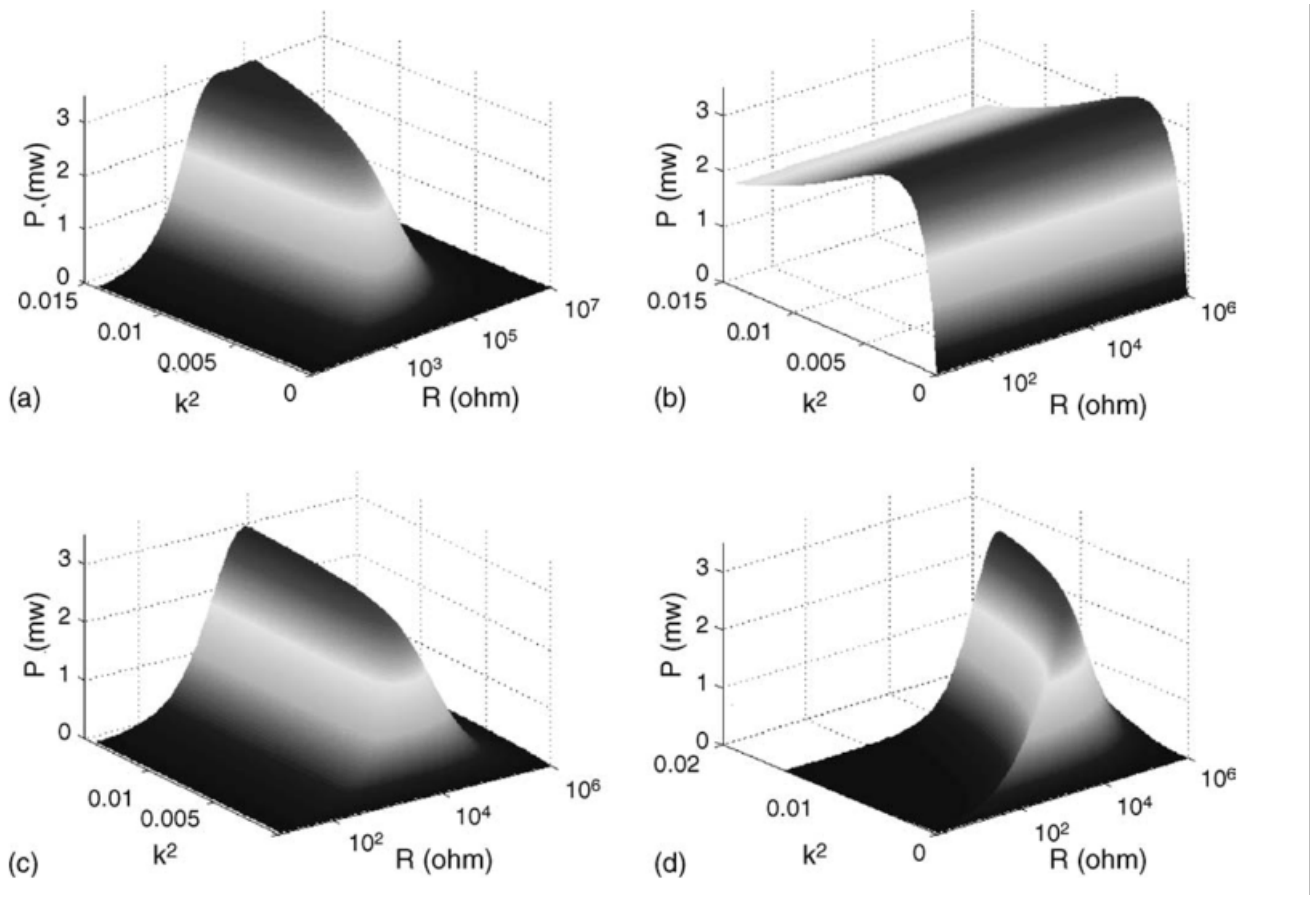
- Max power output

$$P_{max} = \frac{\alpha^2 U_M^2 \omega}{2\pi C_0} \frac{1 + e^{-\frac{\pi}{2Q_i}}}{1 - e^{-\frac{\pi}{2Q_i}}}$$

$$R_{opt} = \frac{\pi}{2\omega C_0} \frac{1 + e^{-\frac{\pi}{2Q_i}}}{1 - e^{-\frac{\pi}{2Q_i}}}$$

Comparison & summary

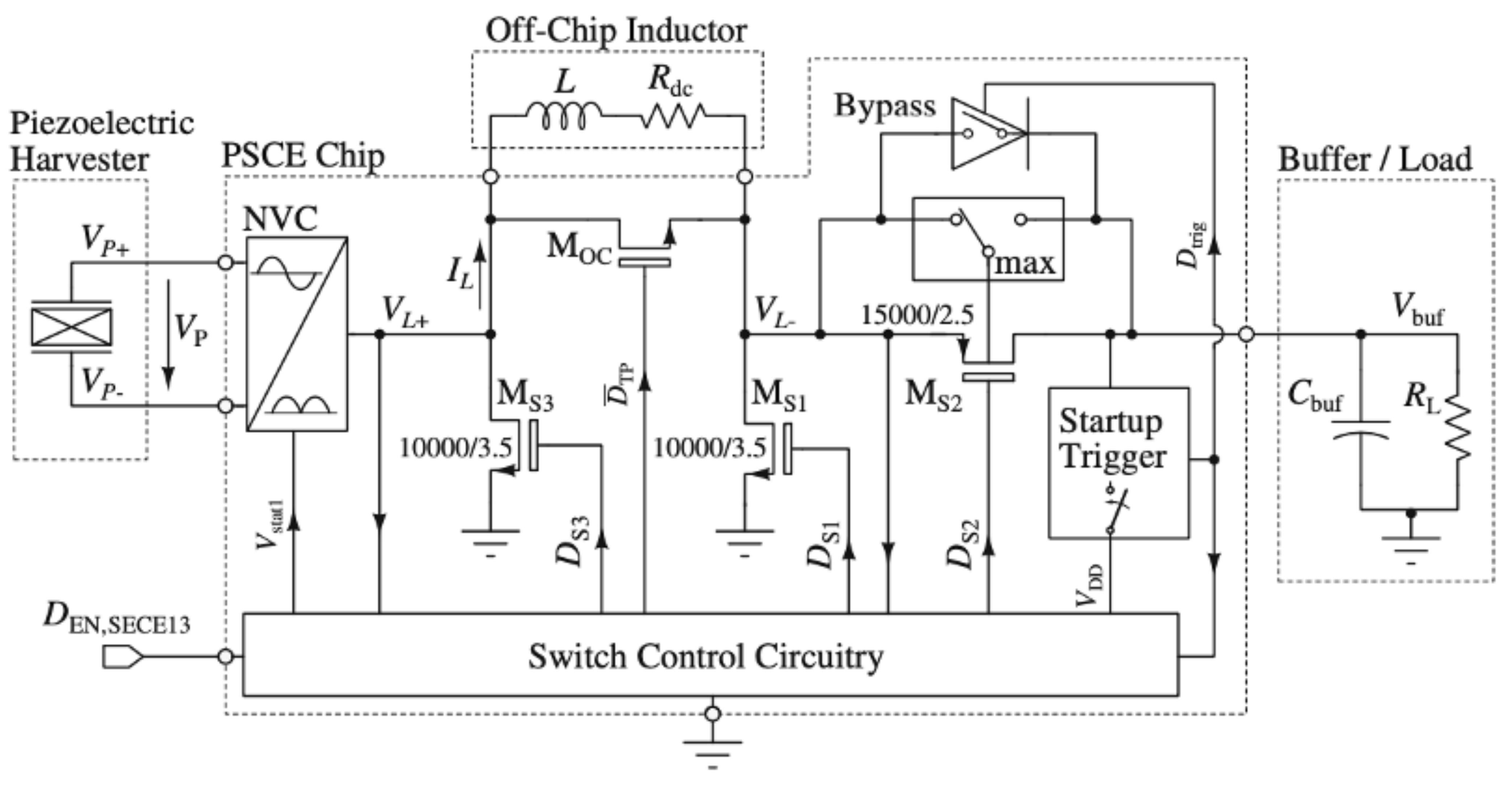
- Energy extraction efficiency



Energy extraction efficiency of interfaces.
(a) Standard interface, (b) SCSE interface,
(c) Series-SSHI interface, (d) Parallel-SSHI interface.

SECE interface implementation

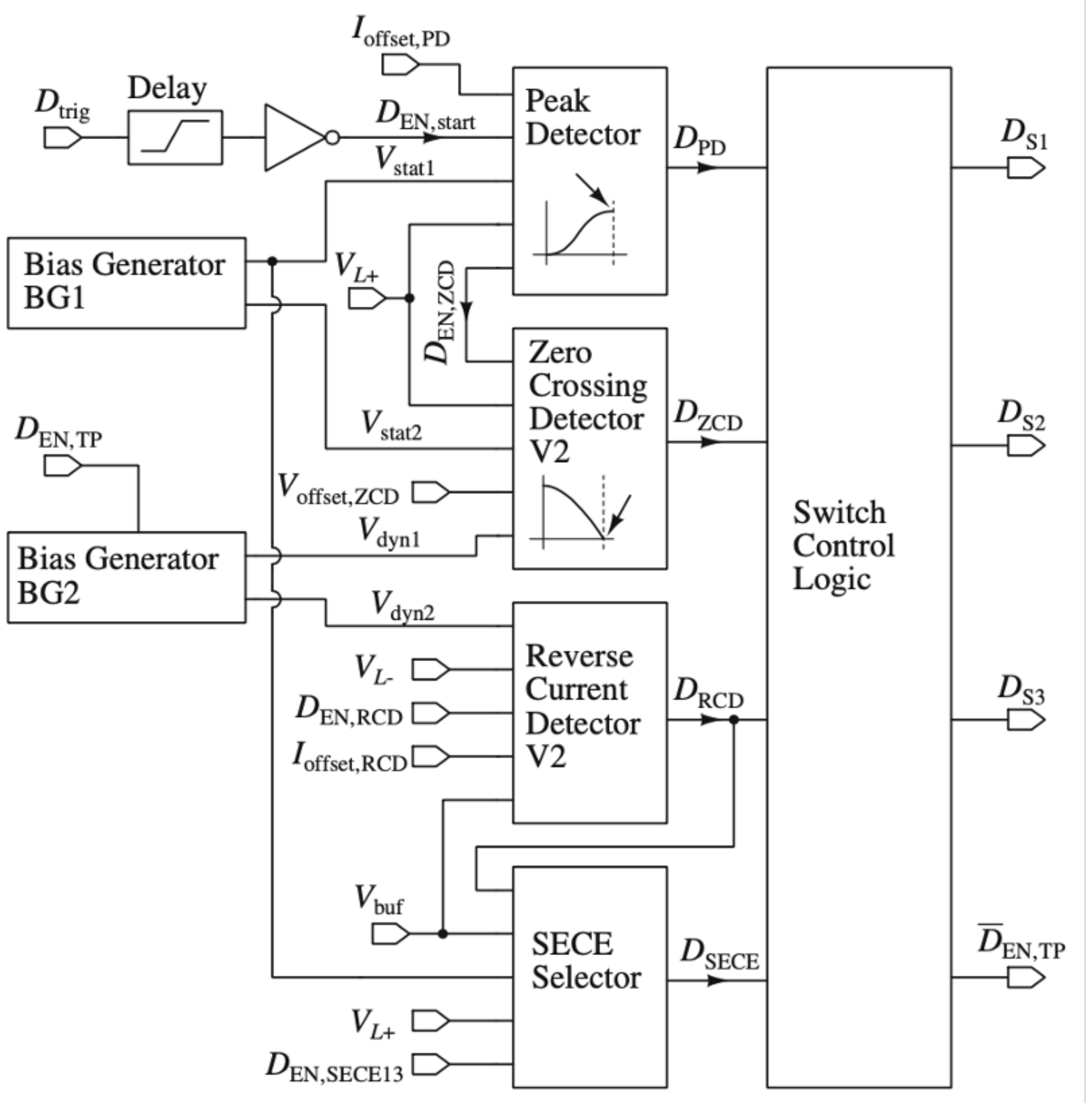
- CMOS implementation of modified SECE interface (PSCE)
- Stable operation insurance measures
  - Oscillation cancellation circuit
  - Novel ZCD architecture
  - Supply-independent biasing



Implementation of SECE interface

SECE interface implementation

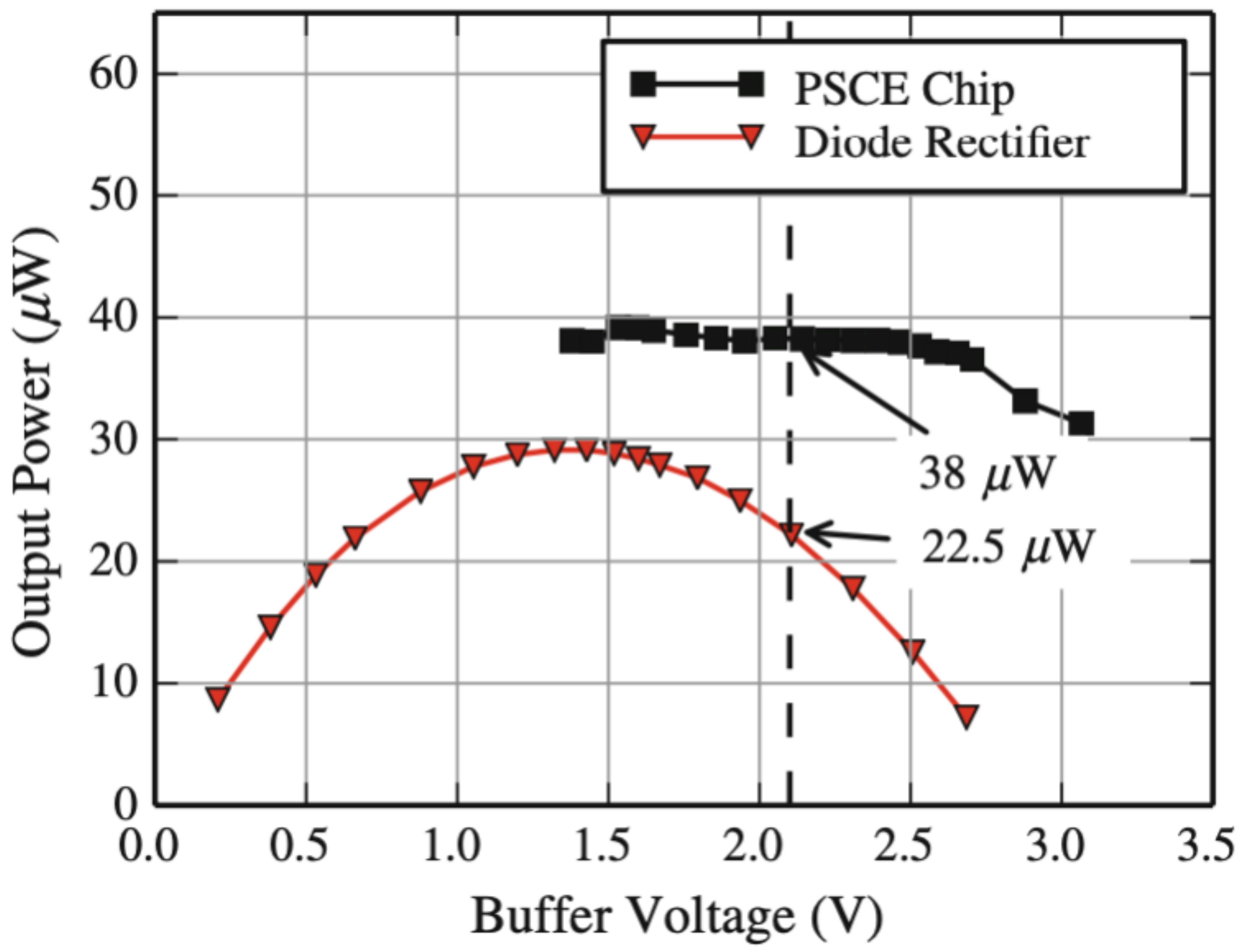
- Switch control circuitry
  - Peak detector
  - Zero crossing detector
  - Reverse current detector
  - SECE selector



Switch control circuitry

SECE interface implementation

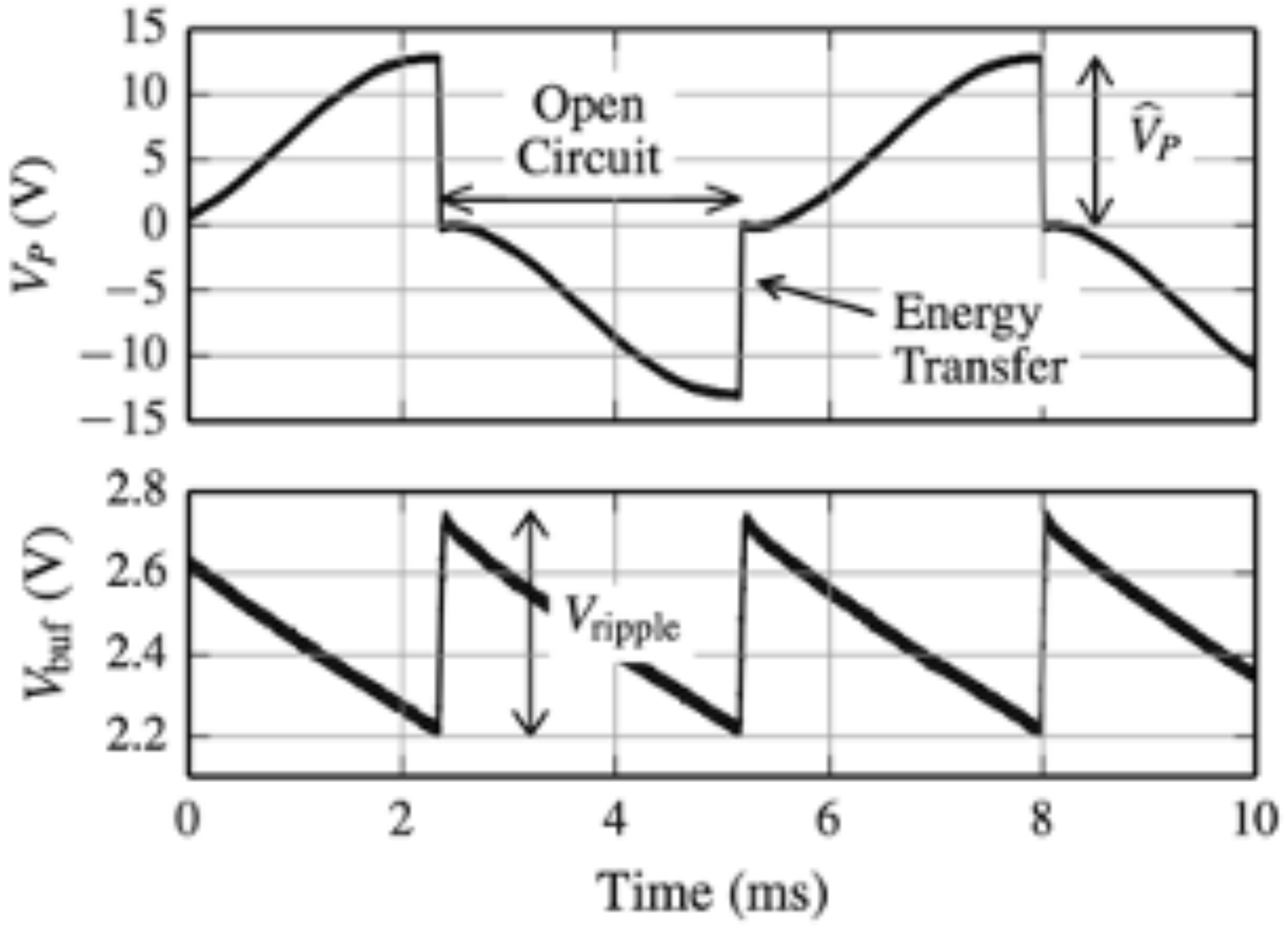
- Simulation result

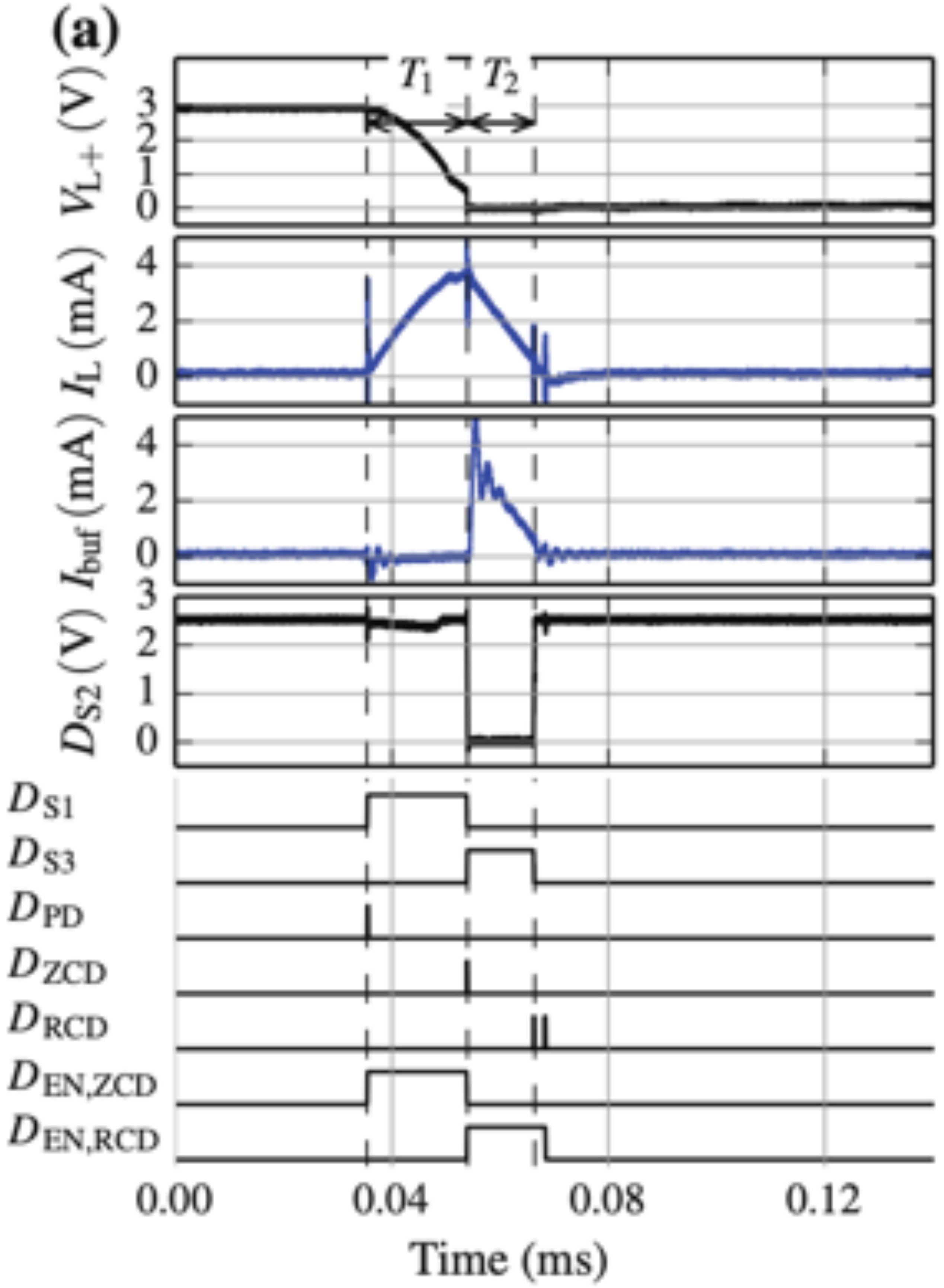


Output power of PSCE chip and standard interface

SECE interface implementation

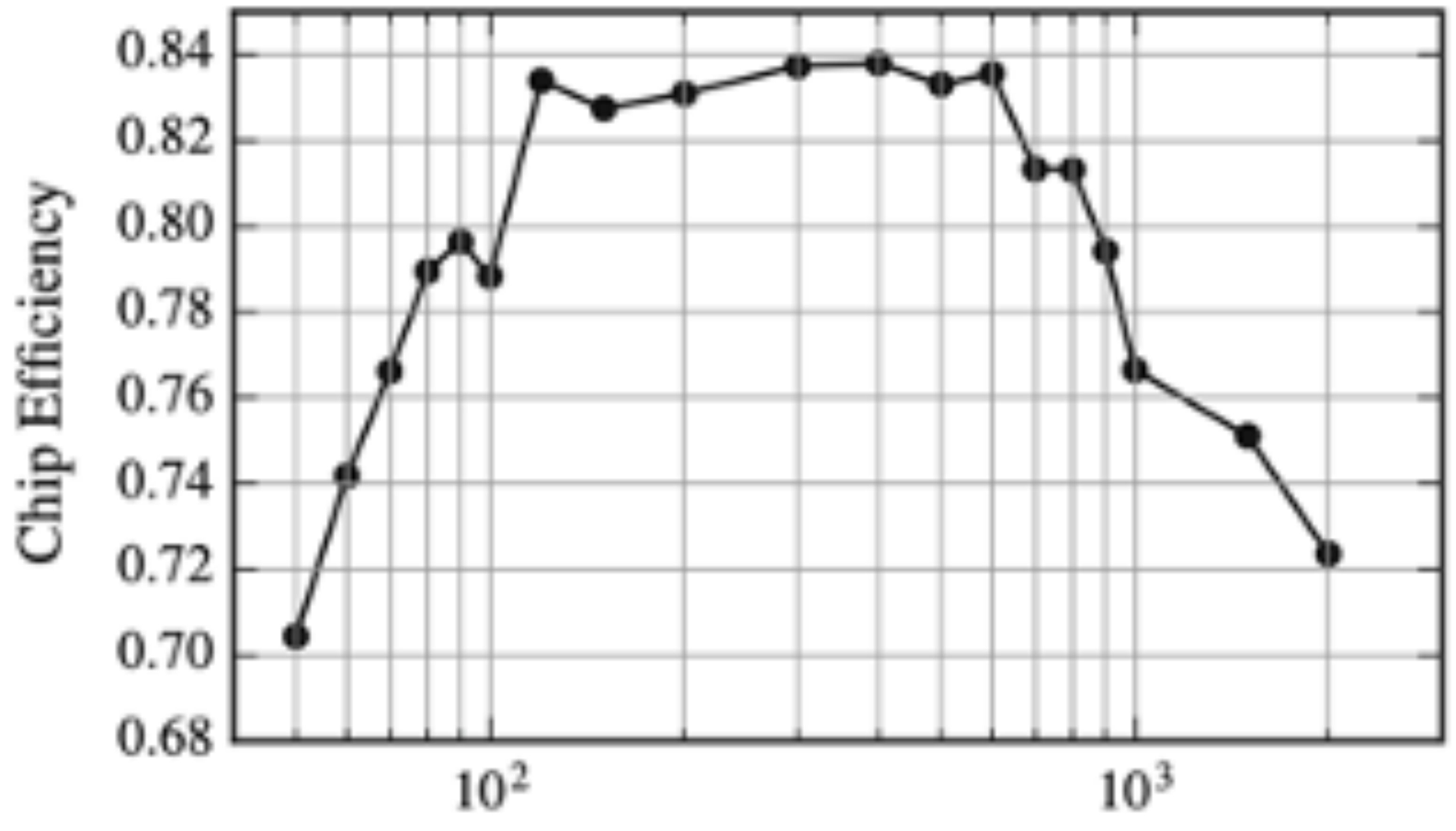
- Simulation result

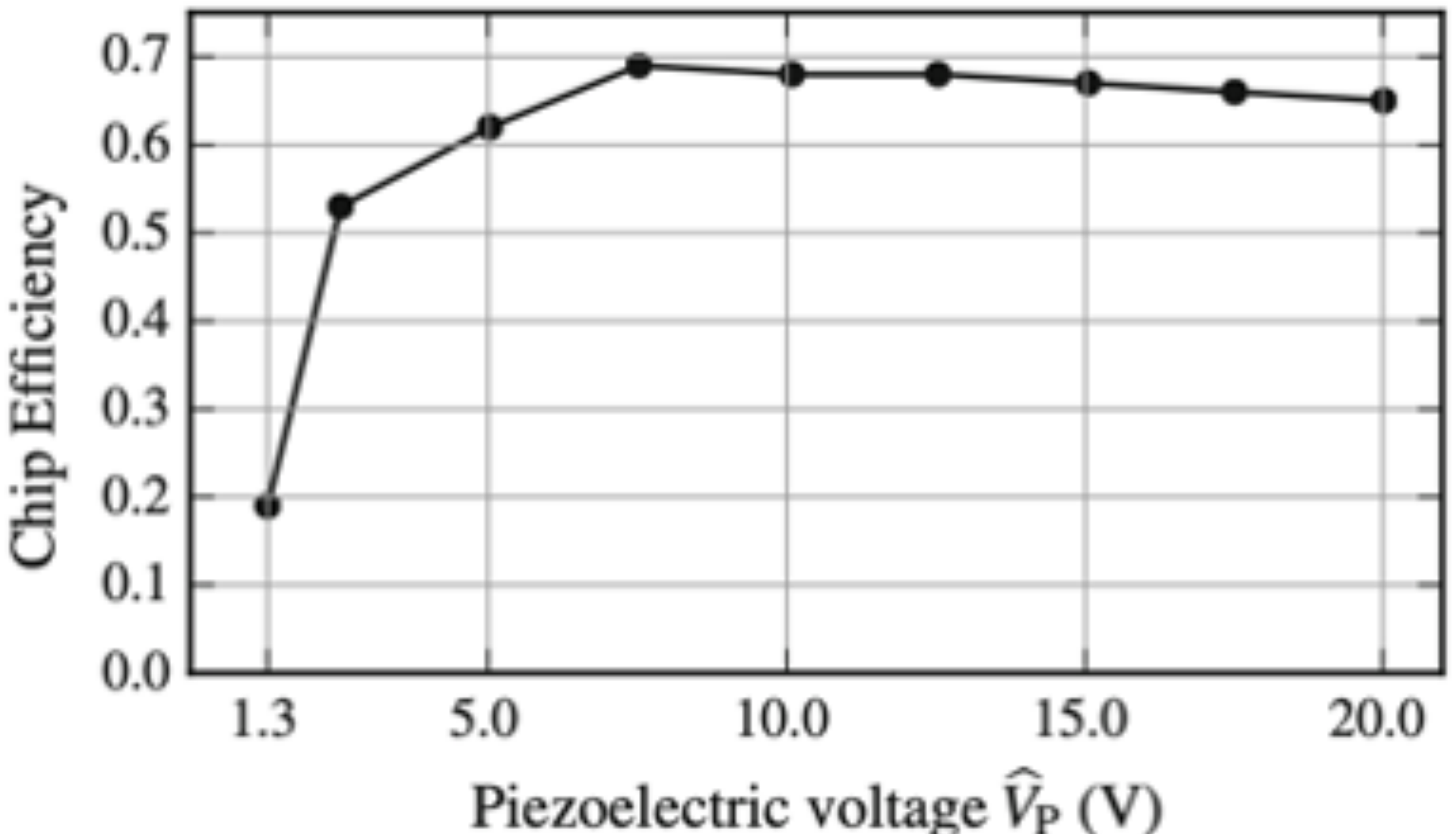


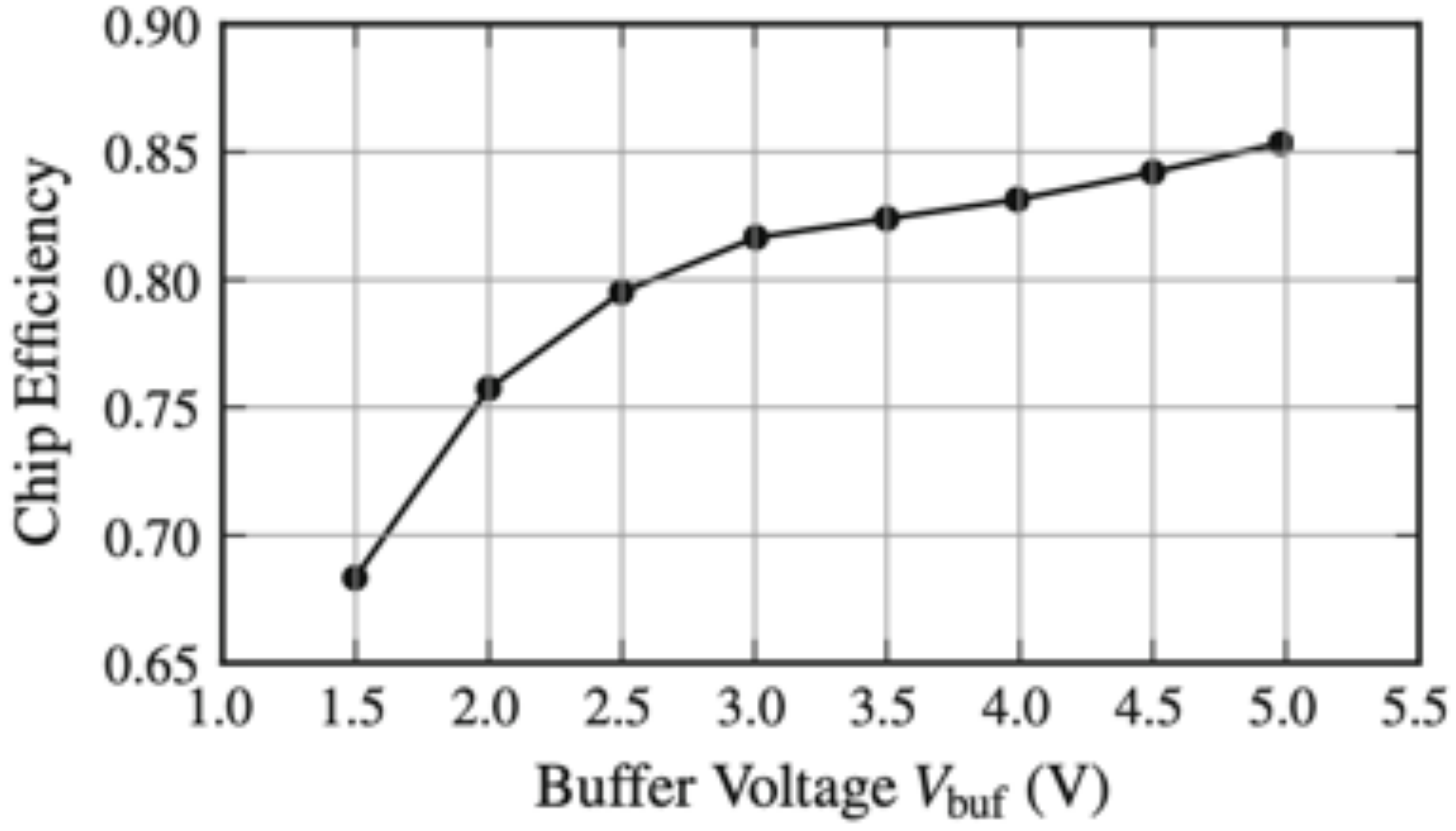


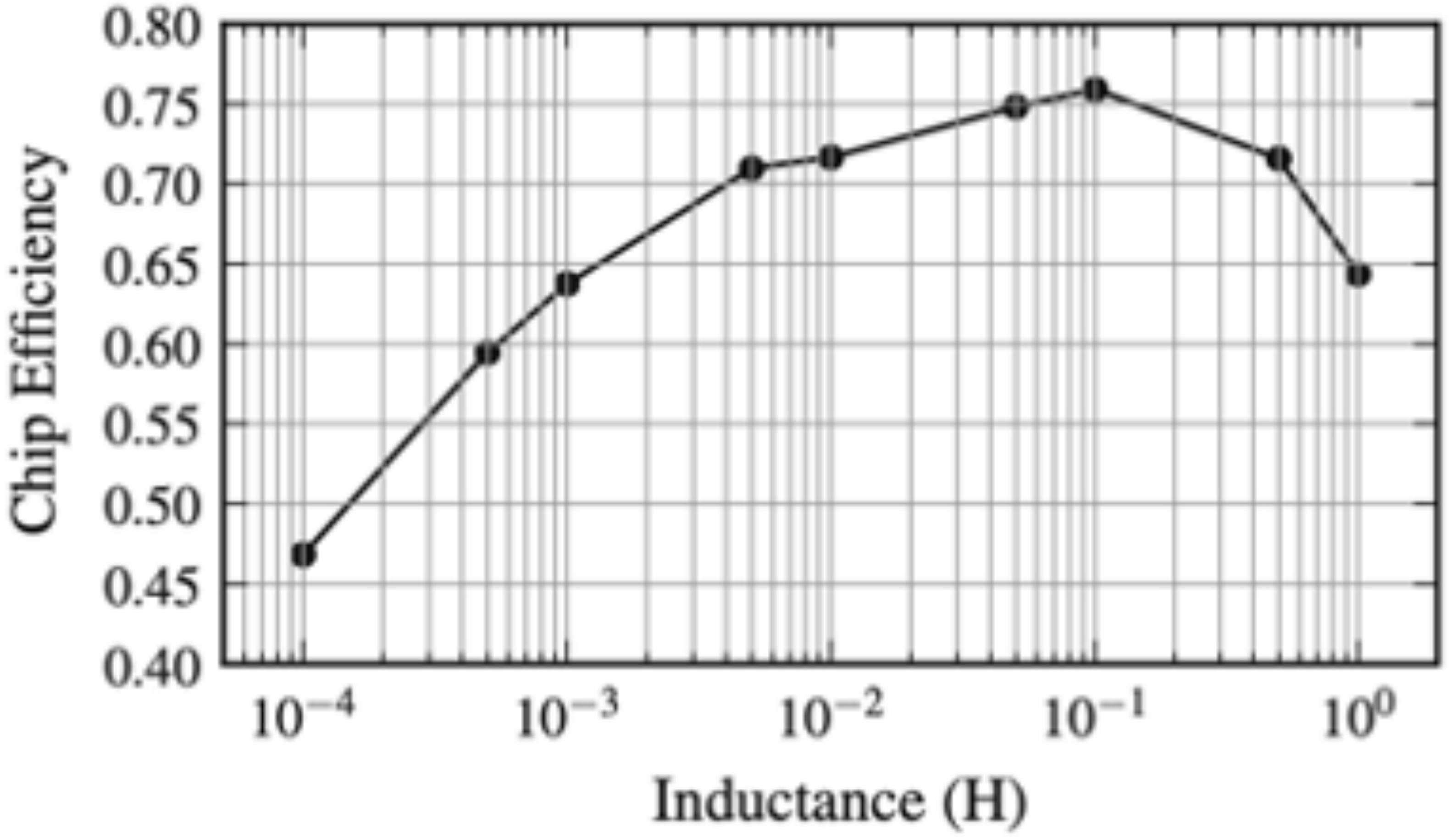
SECE interface implementation

- Simulation result









Summary

- Structure of energy harvesting system
- Several transducers
- Several interface circuits and key parameters
- Implementation of SECE interface

References

- [1] Wikipedia contributors. "Friis transmission equation." *Wikipedia, The Free Encyclopedia*. Wikipedia, The Free Encyclopedia, 6 May. 2021. Web. 24 May. 2021.

- [2] Di Paolo Emilio, M. (2016). Microelectronic circuit design for energy harvesting systems. In *Microelectronic Circuit Design for Energy Harvesting Systems*. https://doi.org/10.1007/978-3-319-47587-5

- [3] Wikipedia contributors. "Piezoelectricity." *Wikipedia, The Free Encyclopedia*. Wikipedia, The Free Encyclopedia, 16 May. 2021. Web. 24 May. 2021.

- [4] WYCShu. (2007). An improved analysis of the SSHI interface in piezoelectric energy harvesting. In *Smart Materials and Structures.*