Energy Harvesting Circuit & Chip

Course project of *Analog Integrated Circuit Design*

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Energy harvesting system

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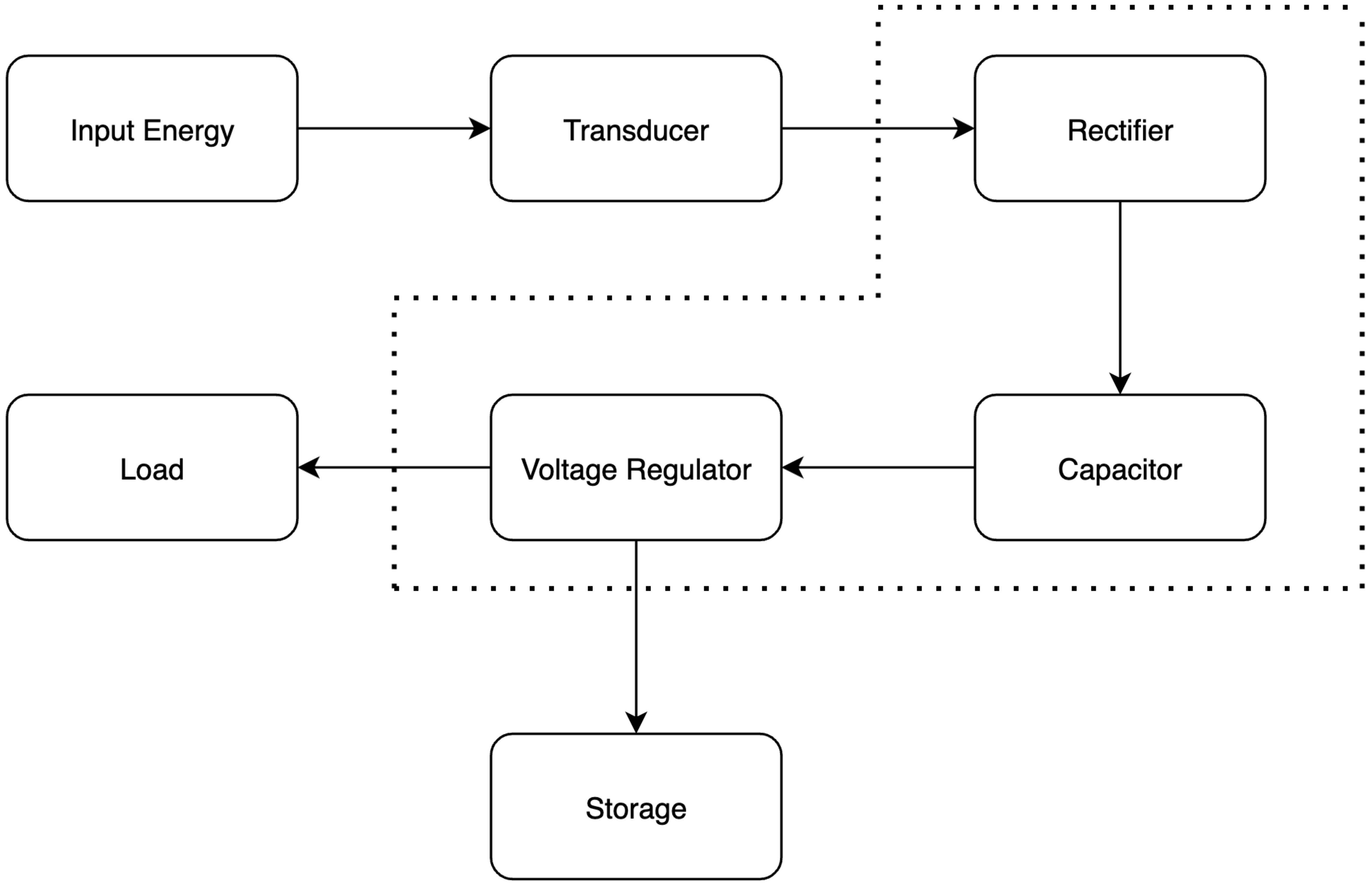
  - Transducer
  - Power management system
  - Load & storage



Transducer

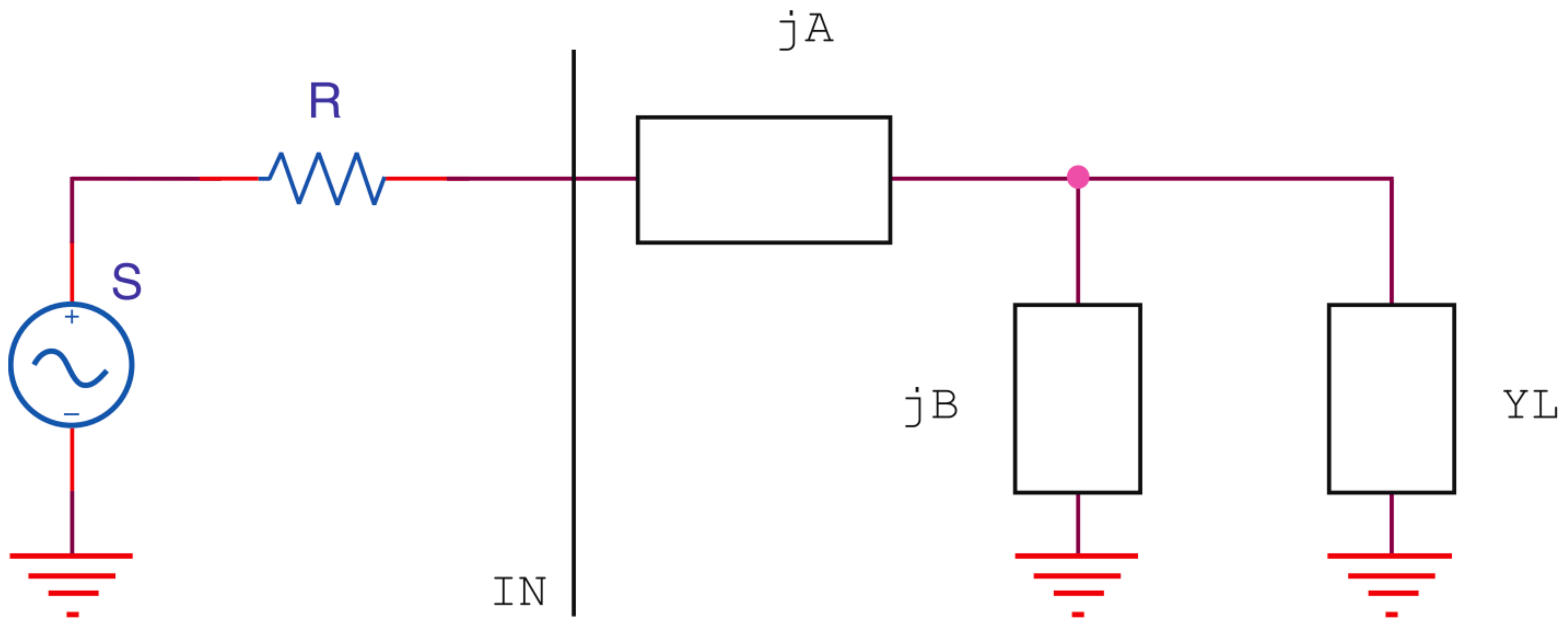
- Convert ambient energy into electrical energy of input
- Ambient energy types
  - RF signal — electromagnetic transducer
  - Vibration — piezoelectric transducer
  - Heat — thermoelectric modules
  - Light — photovoltaic cells
  - …

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]

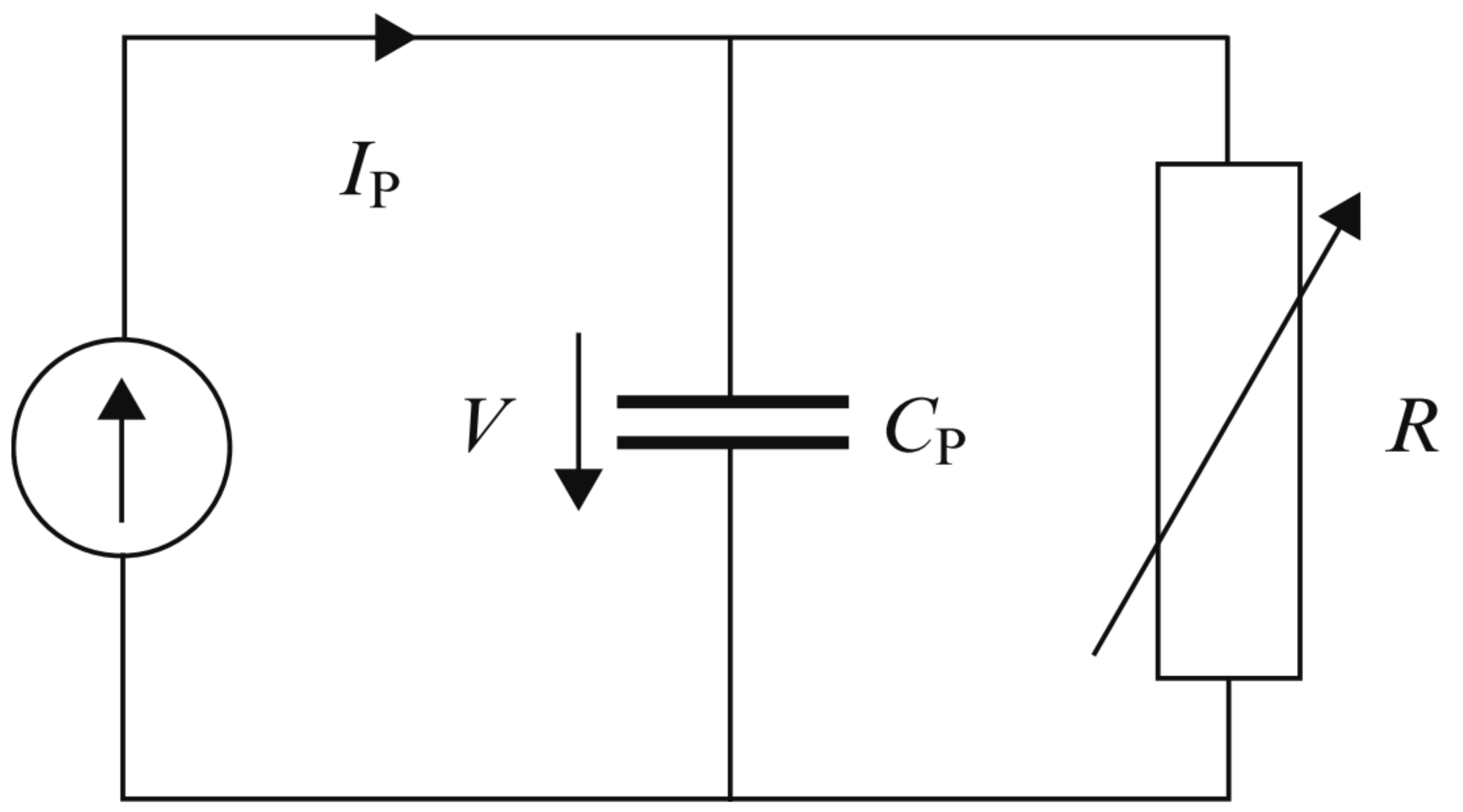
$$v_{out} = \frac{1}{2}\sqrt{1 + Q^2} \times 8R^2P_{inc}$$

- 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

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

Interface circuits

- convert AC to DC
- Optimize the output power
- Decouple the load from the harvest

Efficient AC/DC conversion

- Active/passive
- Full wave/half wave
- Power management system
- low/wide range input voltage

Impedance matching

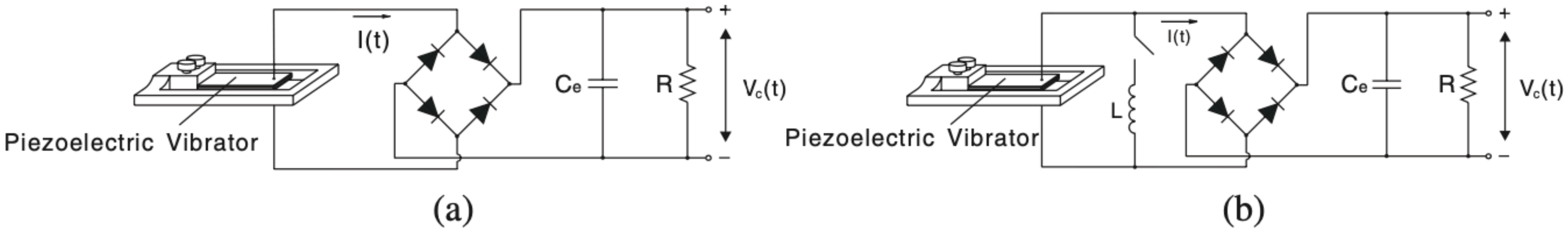
- MPP tracking
- Nonlinear extraction techniques
  - SSHI
  - SECE

Key parameters

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

Article: SSHI analysis

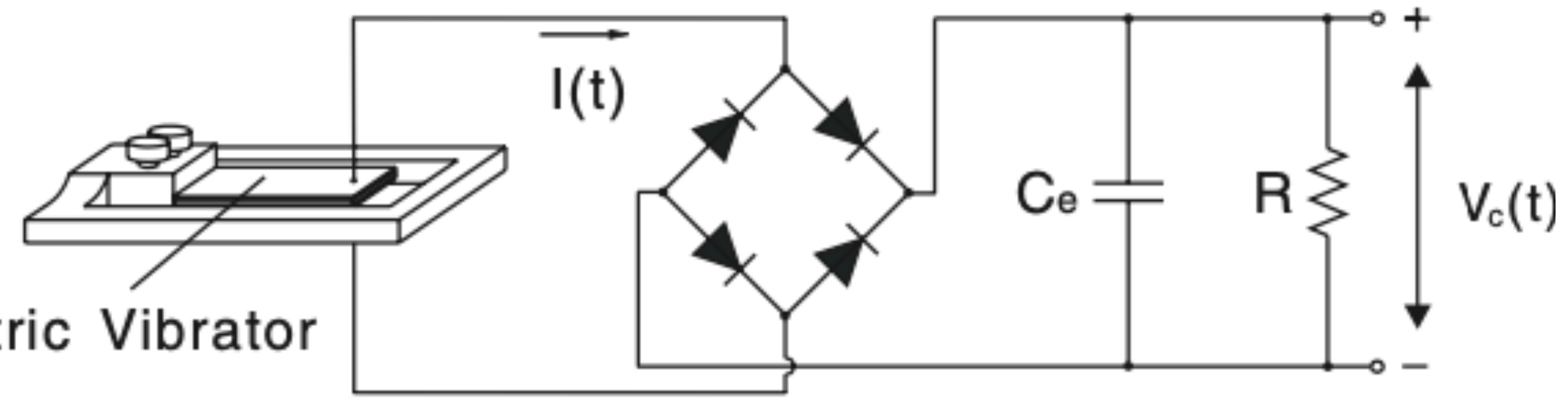
- WYCShu. (2007). An improved analysis of the SSHI interface in piezoelectric energy harvesting. In *Smart Materials and Structures.*
- Till now 344 citations
- SSHI: synchronized switch harvesting on inductor



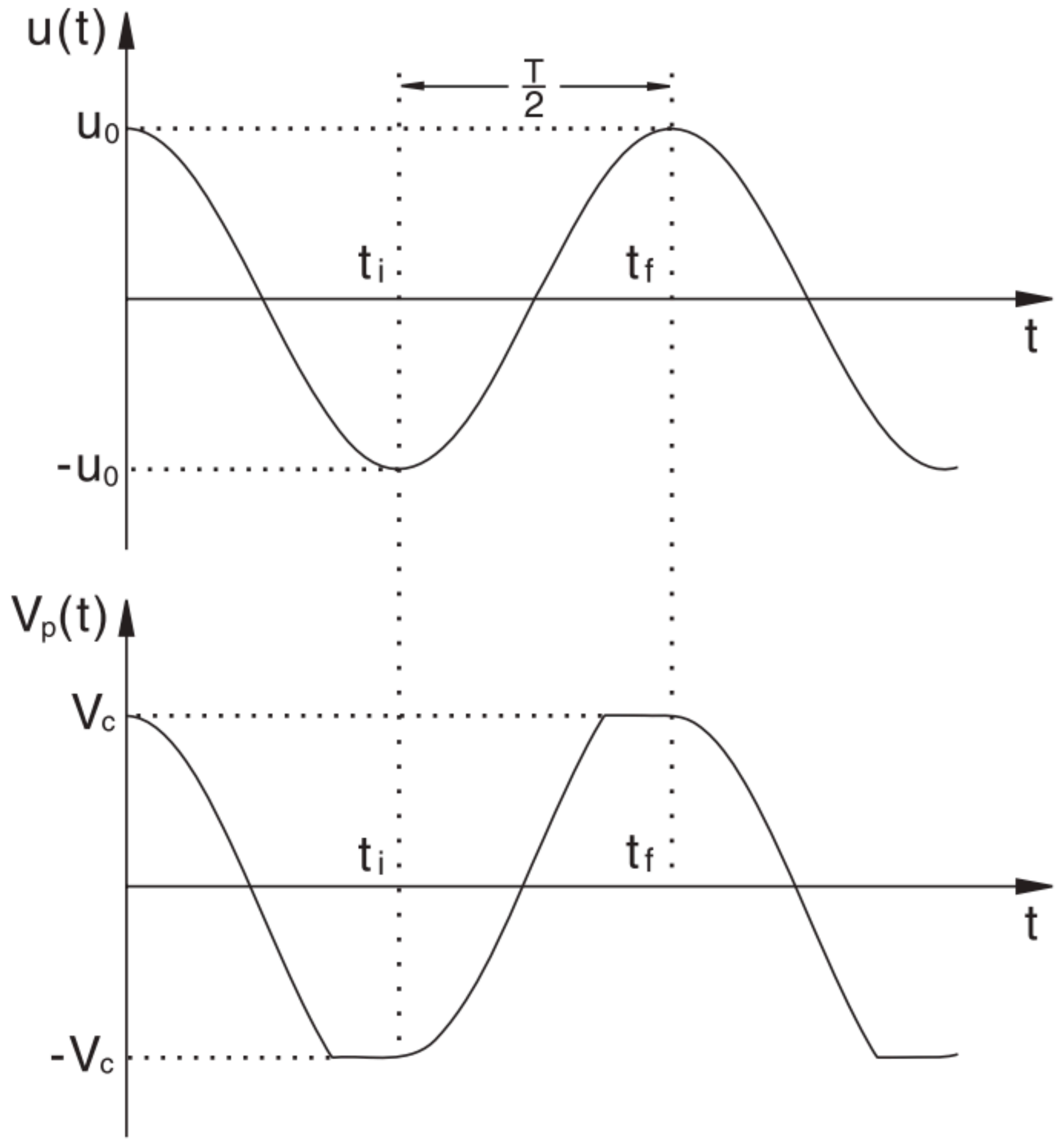
Interface circuit of piezoelectric vibrator. (a): standard interface. (b): SSHI interface

Standard & SSHI interface

- $u(t) = u_0 sin(\omega t + \phi)$
- $V_c = \dfrac{2R\Theta\omega}{2C_pR\omega + \pi}u_0$



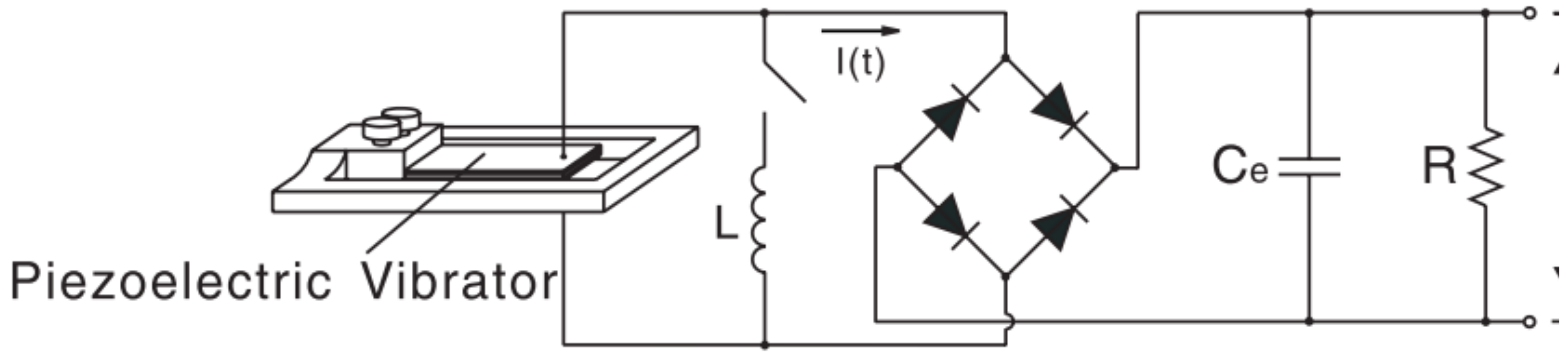
Standard interface circuit



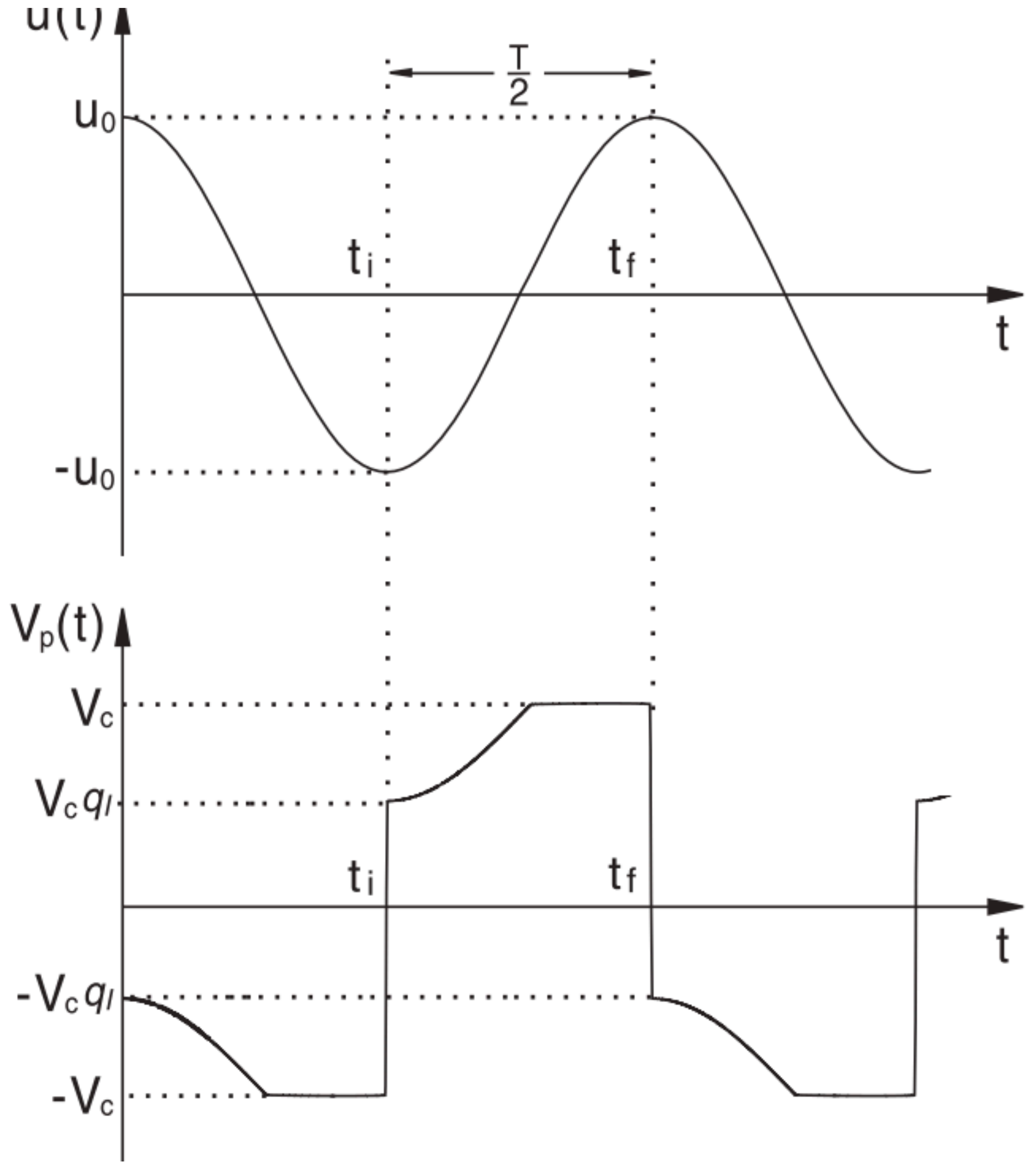
Displacement & output voltage

Standard & SSHI interface

- $V_c = \dfrac{2R\Theta\omega}{(1-q_1)C_pR\omega + \pi}u_0$
- $P = \dfrac{V_c^2}{R} = \dfrac{4R\Theta^2\omega^2}{[(1-q_1)C_1R\omega + \pi]^2}u_0^2$



SSHI interface circuit

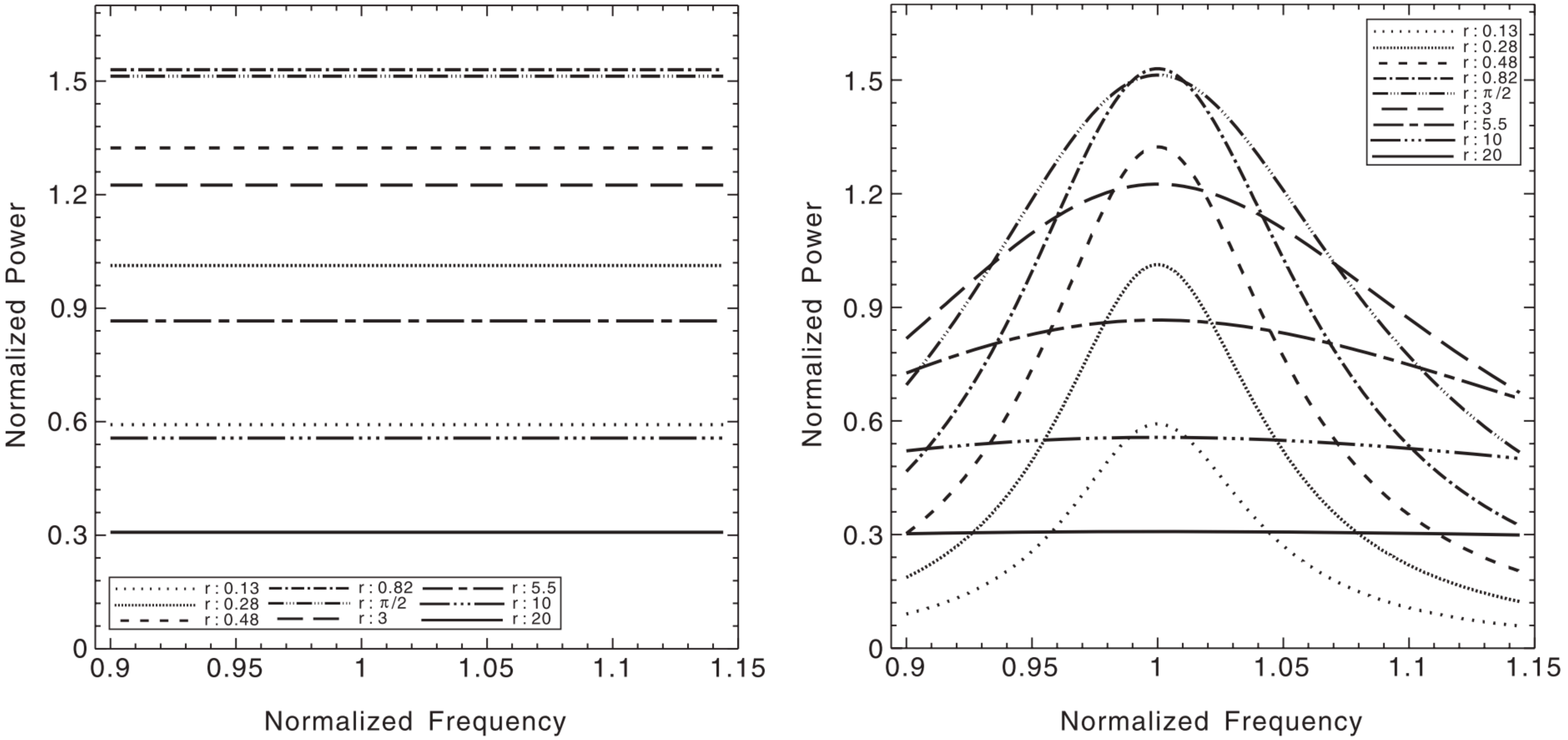


Displacement & output voltage

Assumption & analysis

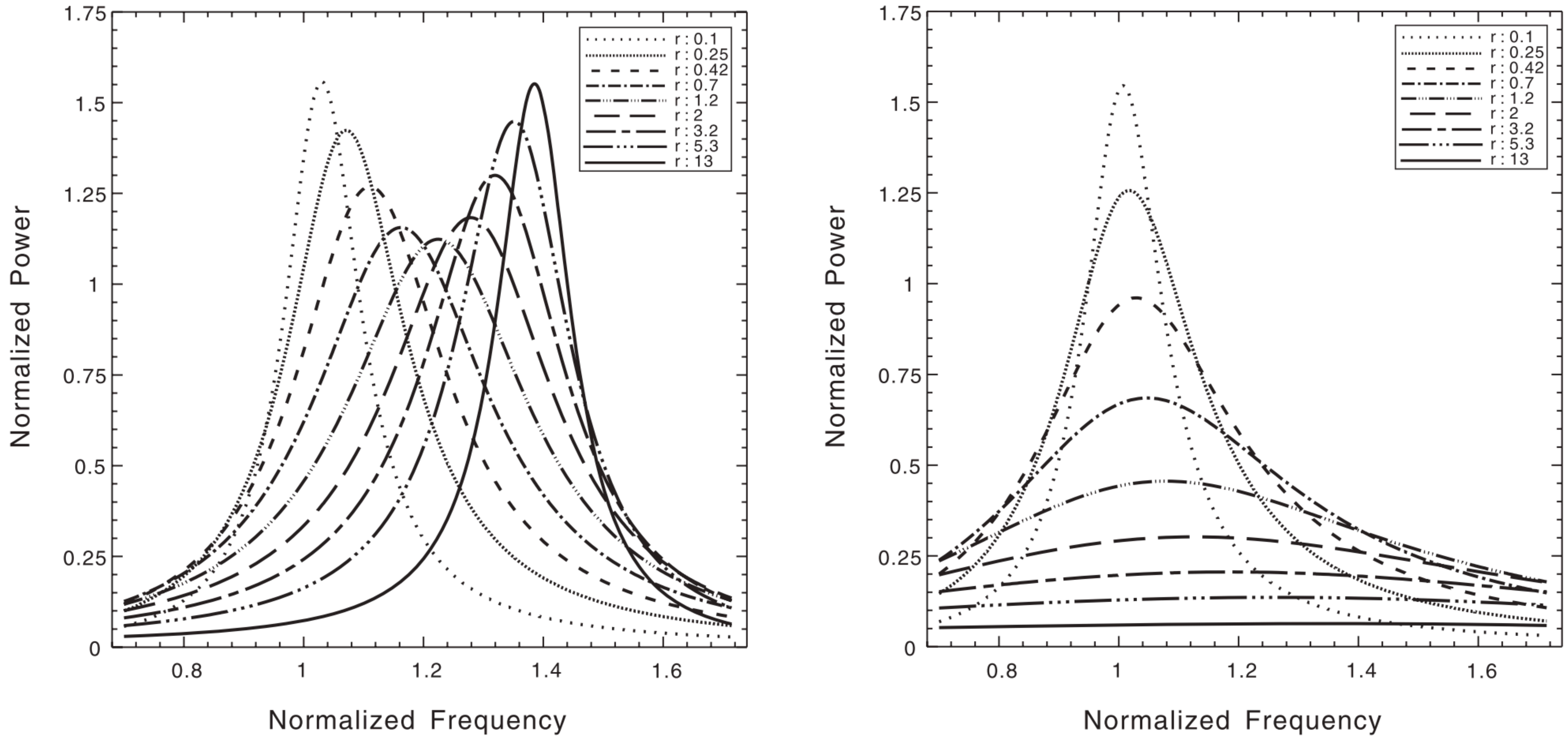
- In-phase assumption analysis
  - Assumes that periodic excitation and the speed of mass are in-phase
  - Lack of frequency dependence
  - Can only predict output power at resonance frequency
- Proposed improved analysis
  - No in-phase assumption
  - Predicts frequency response close to simulation result
  - Can be applied to wide range of frequency

Assumption & analysis



Normalized harvested power versus frequency ratio for various load resistances based on in-phase analysis (left) and proposed improved analysis (right).

Power frequency response



Normalized power versus frequency ratio for different values of normalized resistances. Left is standard interface and right is SSHI 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.*