Th1D-4

Capacitive Wireless Power Transfer Independent of Load Impedance Fluctuation with Transfer Distance

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Outline

- Background
- Proposed Capacitive WPT System for Underwater Drones
- Simulation and Demonstration
- Conclusion

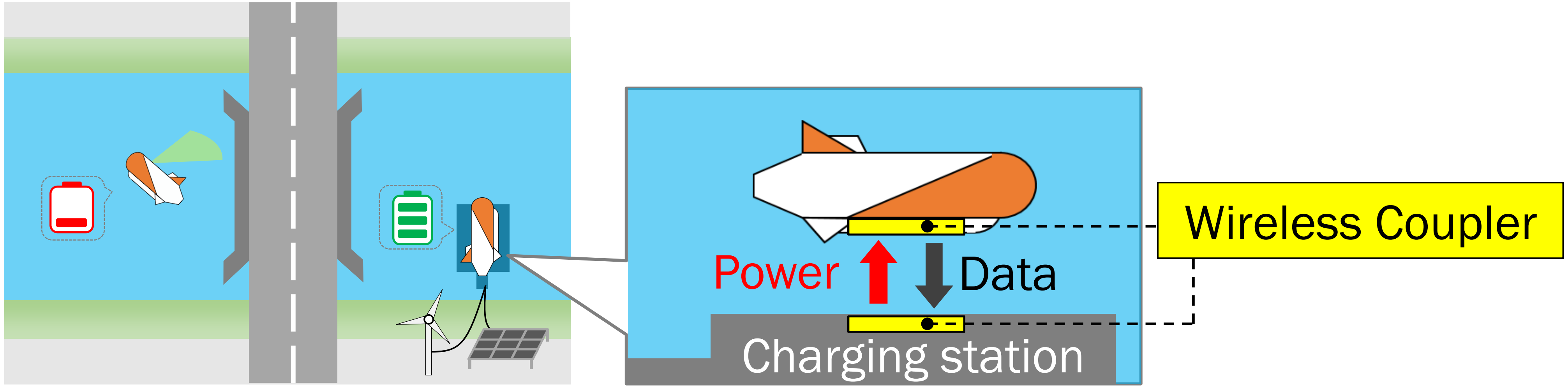
Background

Threat to public safety due to collapses of underwater infrastructures.

→ Unmanned inspection utilizing underwater drones instead of divers[1].

Problem Low operational efficiency due to frequent battery replacement.

Solutions Large-capacity batteries, Underwater wireless power transfer (UWPT)[2].

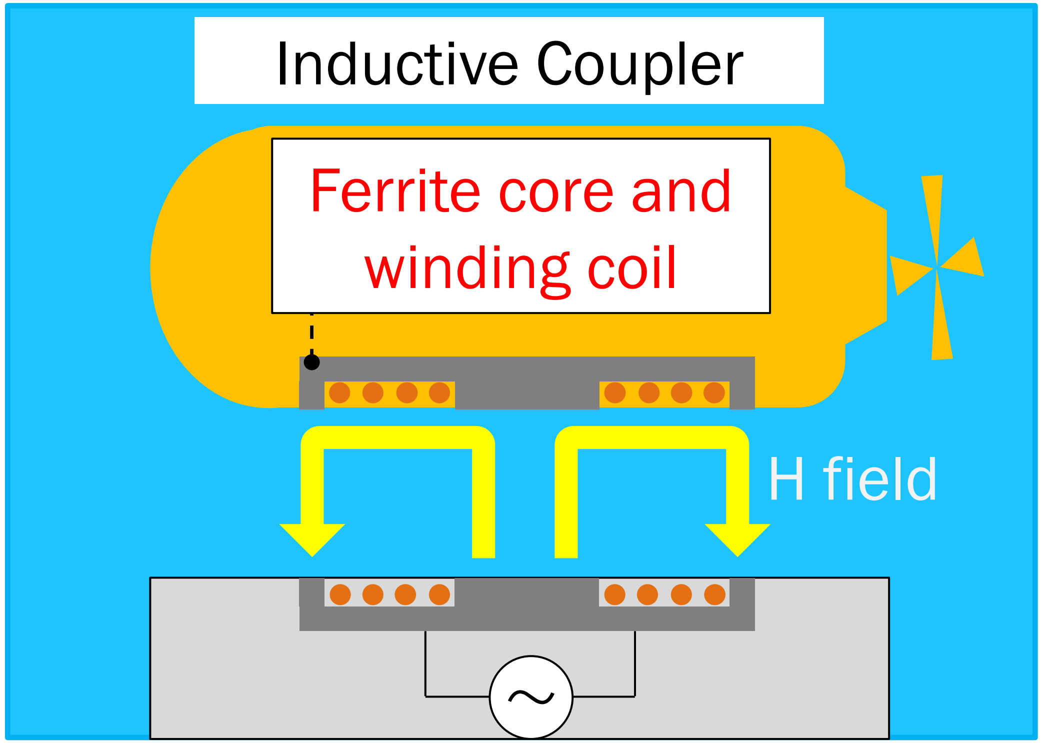


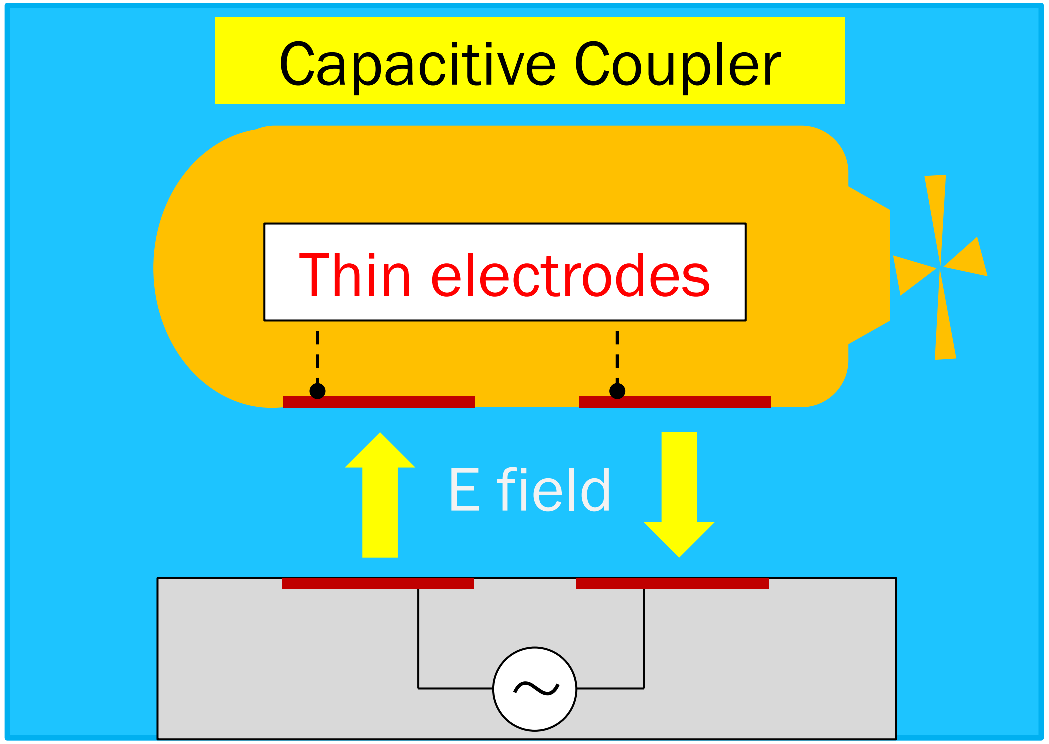
[1] M. Dunbabin, L. Marques, *IEEE Robotics & Automation Magazine*, vol. 19, no. 1, pp. 24–39, Mar. 2012.
[2] C. R. Teeneti, et al., *IEEE Journal of Oceanic Engineering*, vol. 46, no. 1, pp. 68–87, Jan. 2021.

Comparison of Coupler

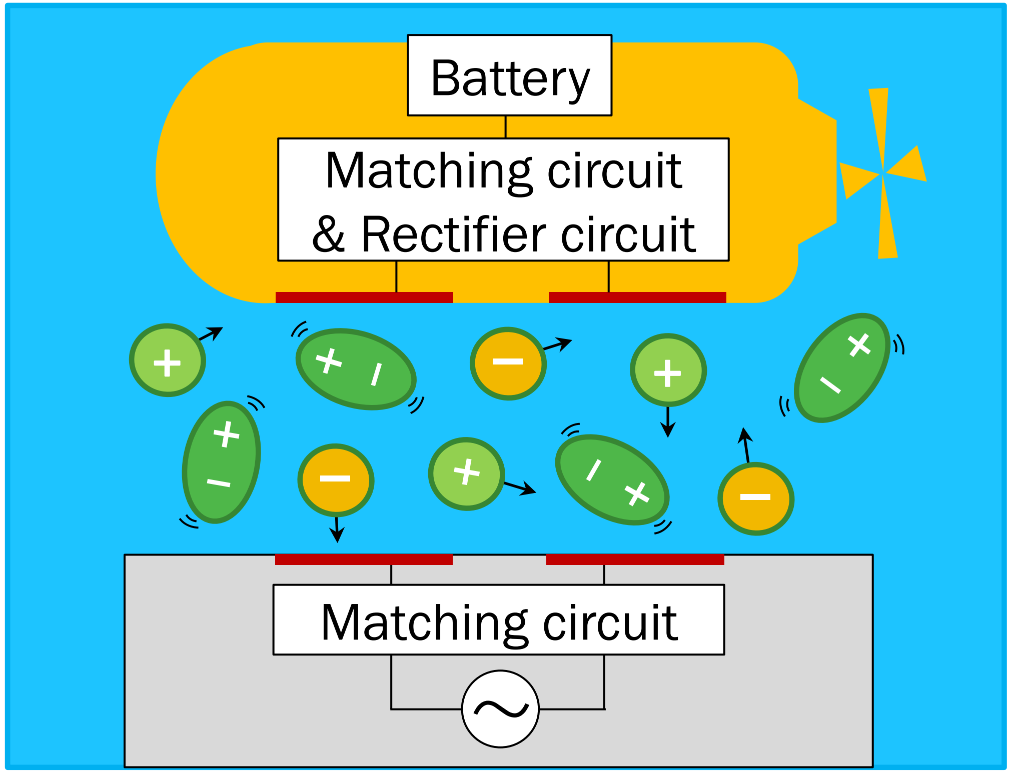
From viewpoint of small payload & easy-moving across obstacles:

✓ Capacitive coupler (lightweight & durable)





Challenges of Capacitive UWPT



1. Attenuation of E-field

Reduced efficiency due to absorption of E-field energy by ions and dipole moments[3].

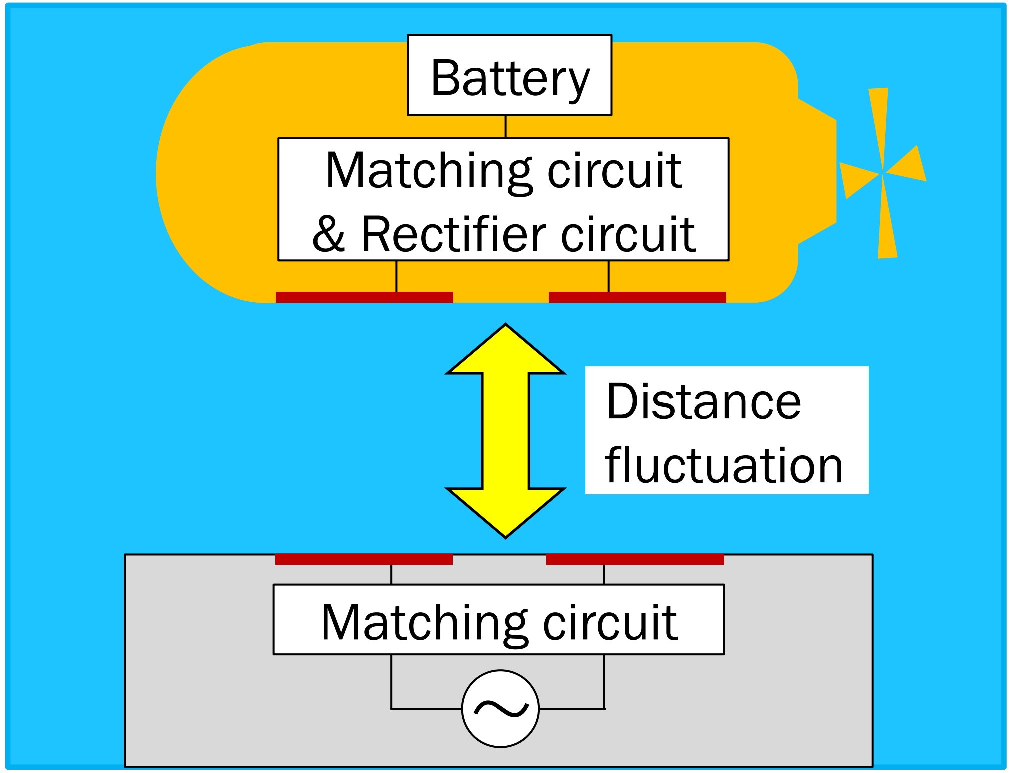
Solutions & Result

- Frequency with maximized efficiency[4]
- Optimizing electrode size and placement[5]

→ **Achievement of 90% power transfer efficiency**

[3] Cost Action IC1301 Team, *IEEE Microwave Magazine*, vol. 18, no. 4, pp. 56–87, June 2017.
[4] Y, Naka, et al., *IEICE Transactions on Electronics*, vol. E100.C, no. 10, pp. 850–857, Oct. 2017.
[5] M. Tamura, et al., *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 12, pp. 5873–5884, Dec. 2018.

Challenges of Capacitive UWPT



2. Impedance Mismatching

Cause: distance fluctuation

→ Impedance mismatch leads to power reflection.

Solutions & Result

- Adaptive matching circuits[6]
- Impedance compression networks[7]

→ **Heaviness & complication of WPT system**

Needs of capacitive UWPT: Straightforward and high-efficient system independent of the distance fluctuation.

[6] S. Jeong, et al., *Proc. of IMS2019*, Boston, MA, USA, June 2019, pp. 1423–1425.
[7] E. Chung, et al., *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 3, no. 3, pp. 432–442, July 2022.

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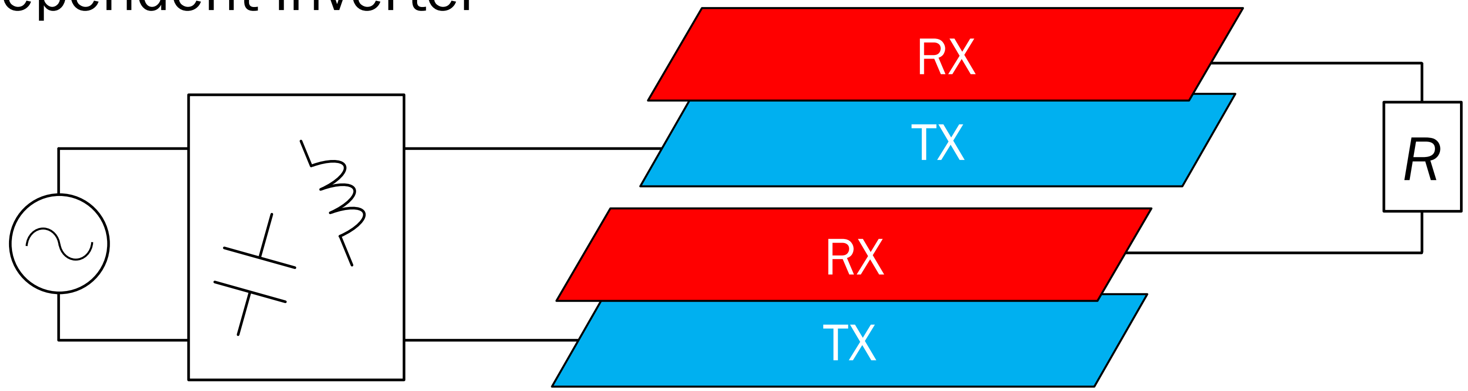
Overview of Proposed System

Simple configuration without matching circuits.

✓ Load-independent inverter

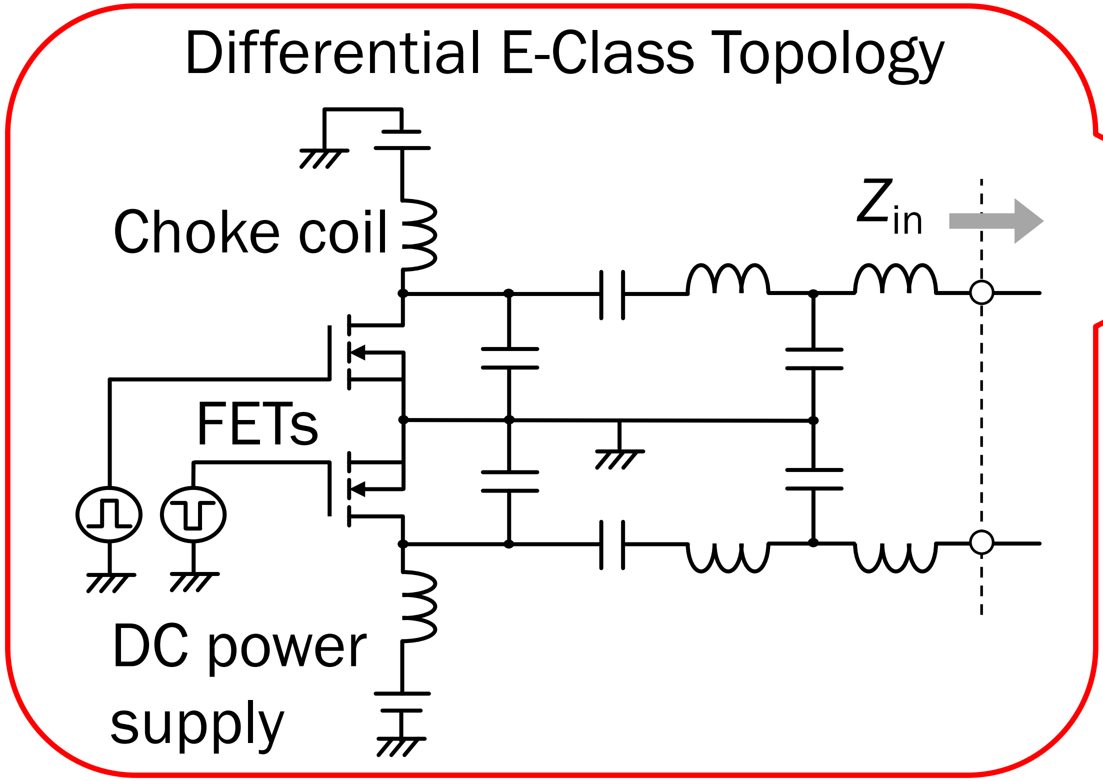


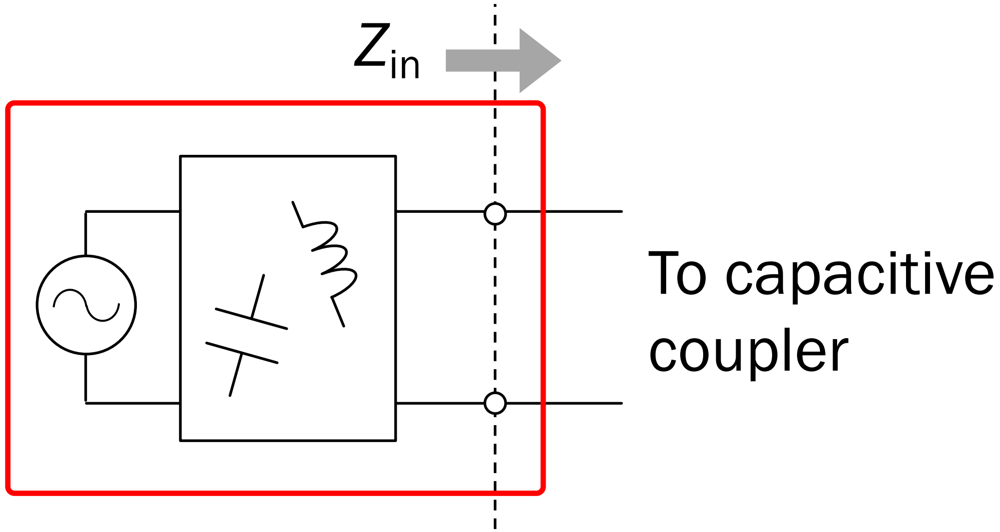
✓ Capacitive coupler with opposite relative position of power feeding/receiving points

Achievement of high-efficient and stable power transmission independent of the distance fluctuation.

Load-independent Inverter

Capable of achieving stable behaviors under low $\mathrm{Im}(Z_{in})$[8, 9]
e.g., Zero-voltage switching (ZVS), Constant-current/-voltage output (CC/CV).





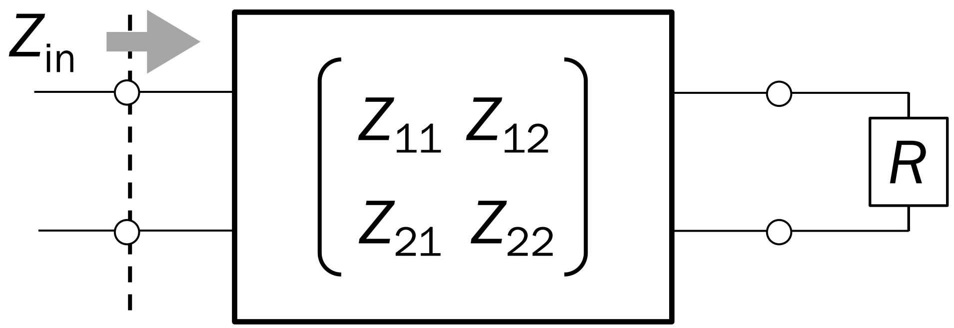
Demands for the coupler:

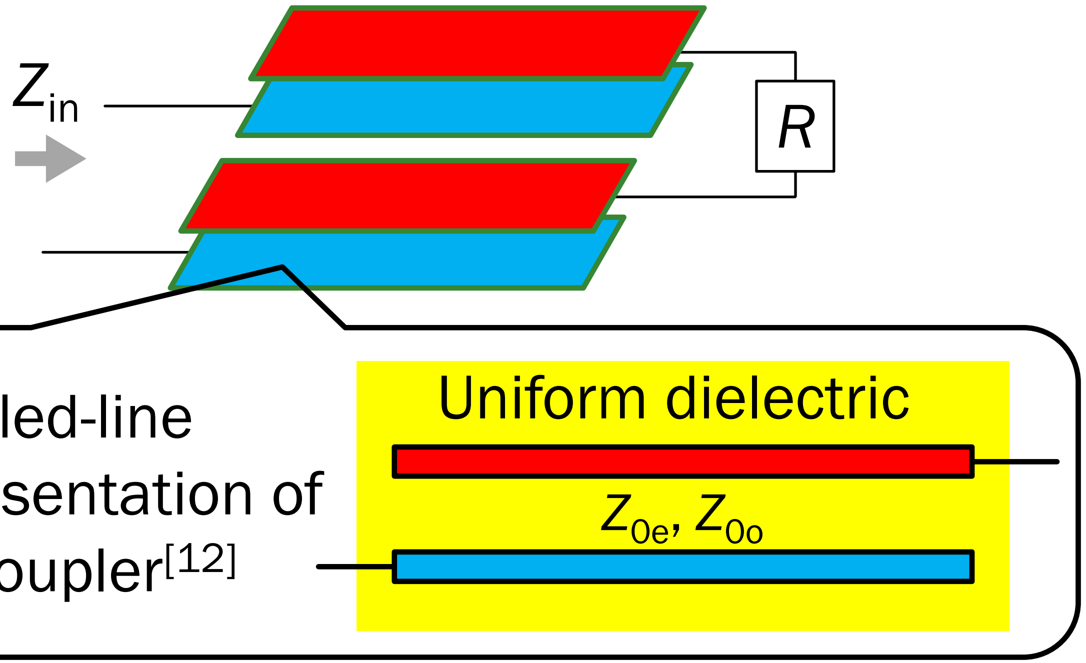
High transfer efficiency & low $\mathrm{Im}(Z_{in})$

[8] M. Mizutani, et al., *Proc. of 2020 IEEE International Conference on Power and Energy*, Dec. 2020, pp. 83–88.
[9] S. Aldhaher, et al., *IEEE Trans. Power Electron.*, vol. 33, no. 10, pp. 8270–8287, Oct. 2018.

η_{max} and Z_{in}

Calculation of maximum achievable efficiency (η_{max})[10, 11] and Z_{in} by Z-matrix of the coupler





η_{max}

$$\eta_{max} = \frac{2}{1 + \sqrt{1 + \chi^2}}$$

$$\chi = \sqrt{\frac{R_{21}^2 + X_{21}^2}{R_{11}R_{22} - R_{21}R_{12}}}$$

Input impedance

$$Z_{in} = Z_{11} - \frac{Z_{12}Z_{21}}{Z_{22} + R}$$

Derivation of Z-matrix elements to simulate the distance fluctuation in water

[10] M. Zargham, P. G. Gulak, *IEEE Trans. Biomed. Circuits and Syst.*, vol. 6, no. 3, pp. 228–245, June 2012.
[11] T. Ohira, *IEICE Transactions on Electronics*, vol. E101.C, no. 10, pp. 719–726, Oct. 2018.
[12] Y. Naka, M. Tamura, *IEICE Communication Express*, vol. 9, no. 10, pp. 457–463, Oct. 2020.

Derived Z-matrix Elements

$$Z_{11} = \frac{1}{2\omega\sqrt{1+Q_d^{-2}}}\left(\frac{1}{C_e}+\frac{1}{C_o}\right)(A+jB)$$

$$Z_{21} = \frac{1}{2\omega\sqrt{1+Q_d^{-2}}}\left(\frac{1}{C_e}-\frac{1}{C_o}\right)(C+jD)$$

$^*\gamma = \alpha + j\beta$

$$A = \left\{\alpha\cos\left(\tan^{-1}Q_d\right)+\beta\sin\left(\tan^{-1}Q_d\right)\right\}\mathrm{Re}(\coth\gamma l)-\left\{\beta\cos\left(\tan^{-1}Q_d\right)-\alpha\sin\left(\tan^{-1}Q_d\right)\right\}\mathrm{Im}(\coth\gamma l)$$

$$B = \left\{\alpha\cos\left(\tan^{-1}Q_d\right)+\beta\sin\left(\tan^{-1}Q_d\right)\right\}\mathrm{Im}(\coth\gamma l)+\left\{\beta\cos\left(\tan^{-1}Q_d\right)-\alpha\sin\left(\tan^{-1}Q_d\right)\right\}\mathrm{Re}(\coth\gamma l)$$

$$C = \left\{\alpha\cos\left(\tan^{-1}Q_d\right)+\beta\sin\left(\tan^{-1}Q_d\right)\right\}\mathrm{Re}(\mathrm{csch}\,\gamma l)-\left\{\beta\cos\left(\tan^{-1}Q_d\right)-\alpha\sin\left(\tan^{-1}Q_d\right)\right\}\mathrm{Im}(\mathrm{csch}\,\gamma l)$$

$$D = \left\{\alpha\cos\left(\tan^{-1}Q_d\right)+\beta\sin\left(\tan^{-1}Q_d\right)\right\}\mathrm{Im}(\mathrm{csch}\,\gamma l)+\left\{\beta\cos\left(\tan^{-1}Q_d\right)-\alpha\sin\left(\tan^{-1}Q_d\right)\right\}\mathrm{Re}(\mathrm{csch}\,\gamma l)$$

Conversion from even-/odd-mode capacitances to coupling coefficient

$$k = \frac{C_o - C_e}{C_o + C_e}$$

Dependence of η_{max} and Z_{in} on ***k*, Q factor of dielectric, line length, and load.**

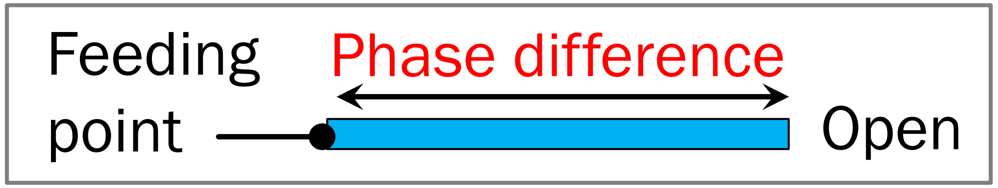
k = 0.2, 0.5, 0.8 → Distance fluctuation, Q_d (ε_r = 79, σ = 0.013 S/m) → Tap water.

Line length of 610 mm, and load resistance of 25 Ω.

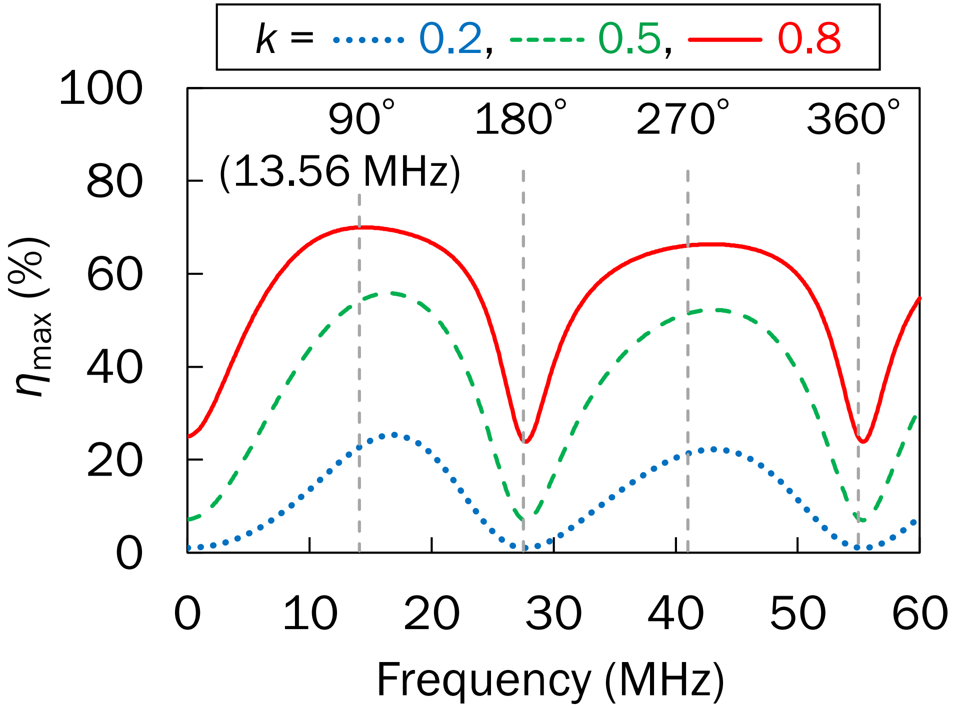
Numerical Analysis

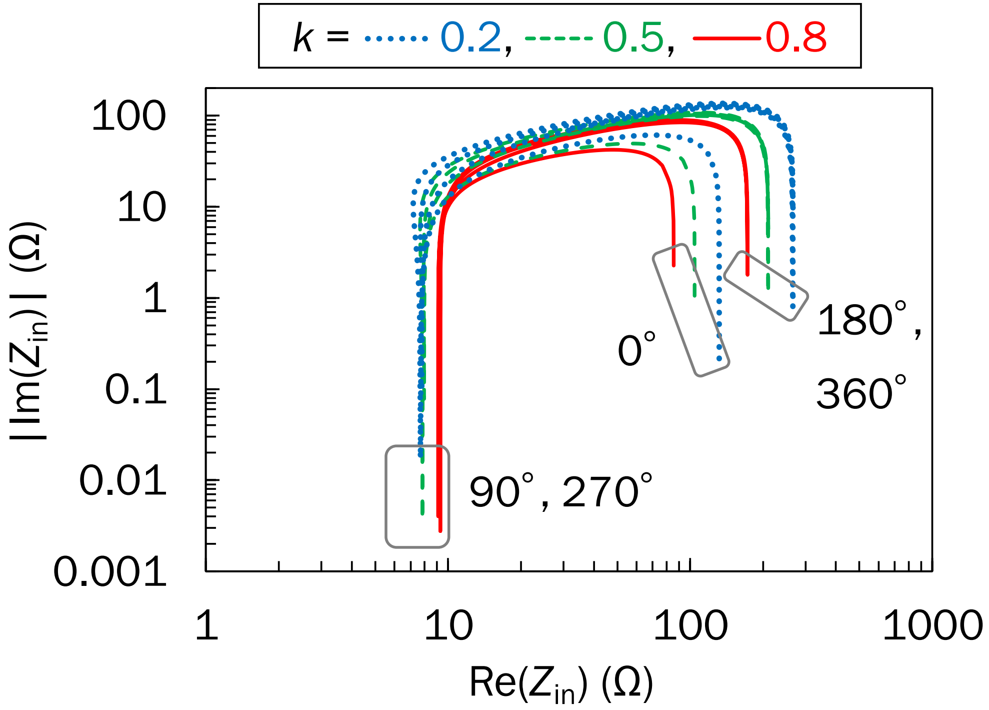
Fulfillment of the demands due to the phase difference of 90° & 270°

→ Phase difference of 90° (13.56 MHz: *ISM bands)



*Industrial, Scientific and Medical band





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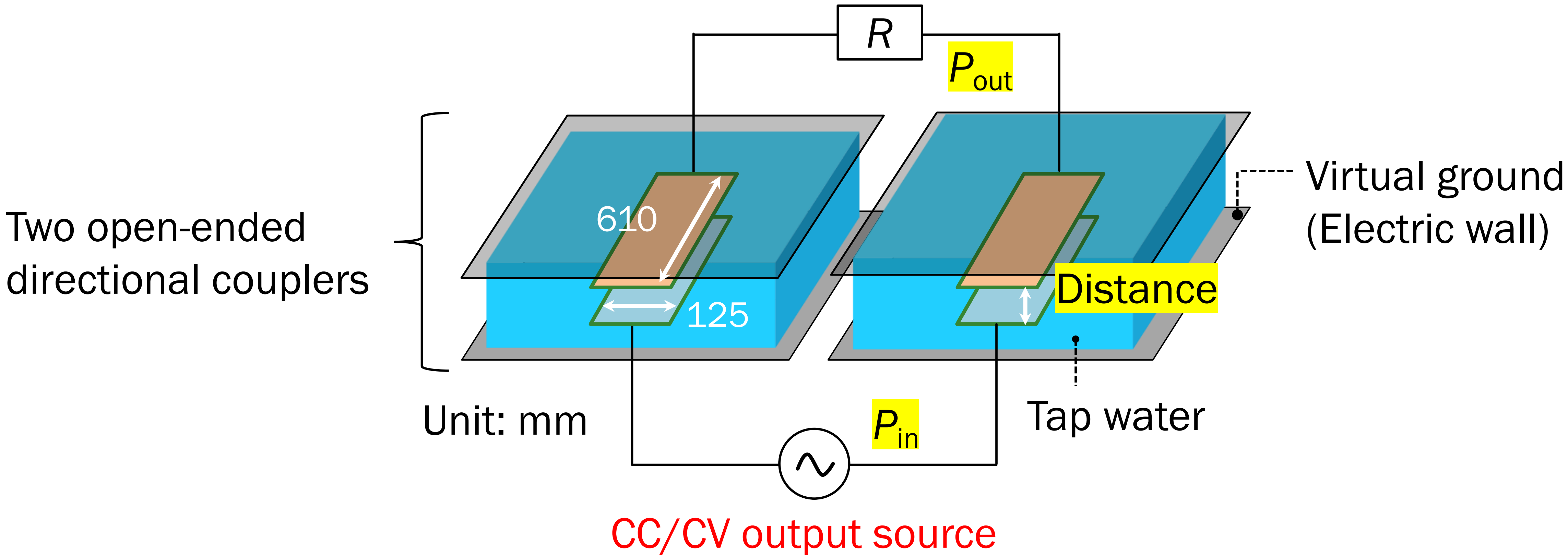
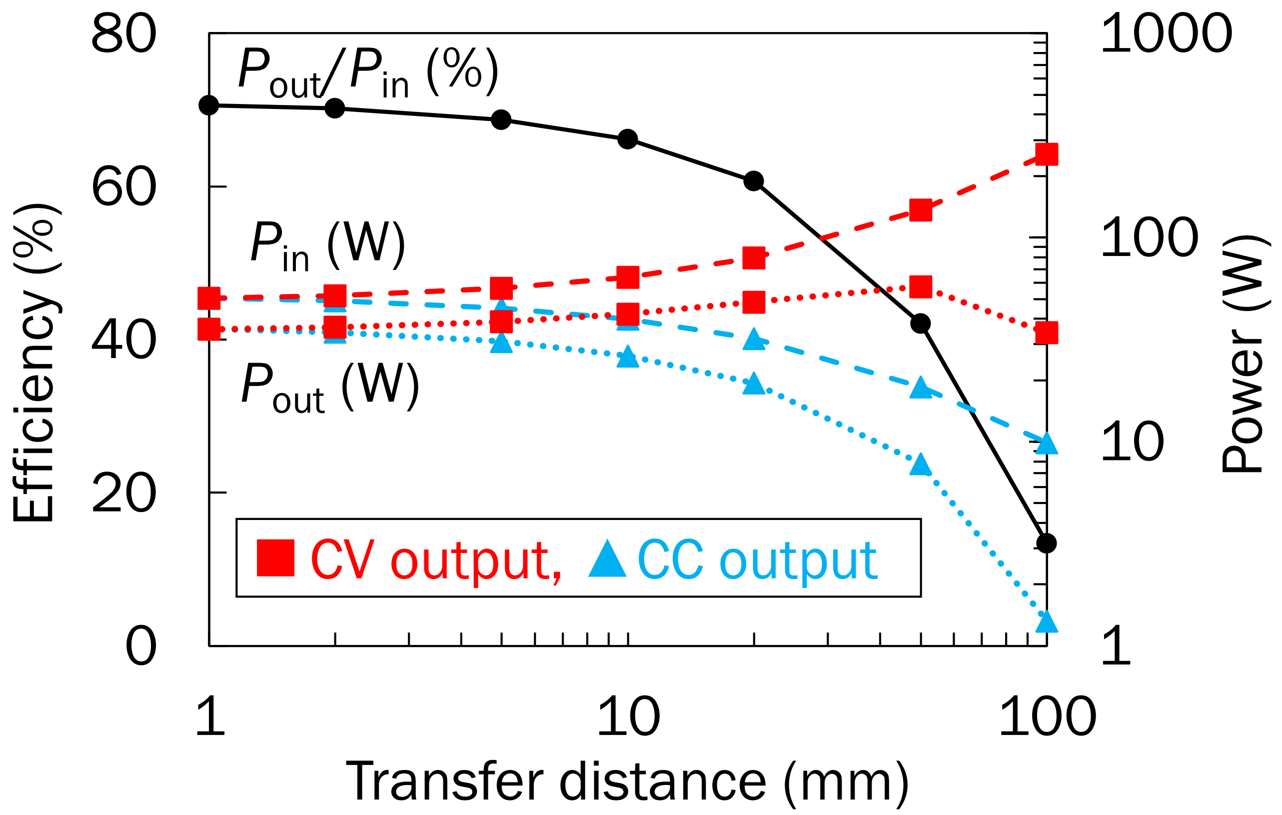
Simulation Setup



Calculation of input/output power for each operation at 13.56 MHz

Simulated Result

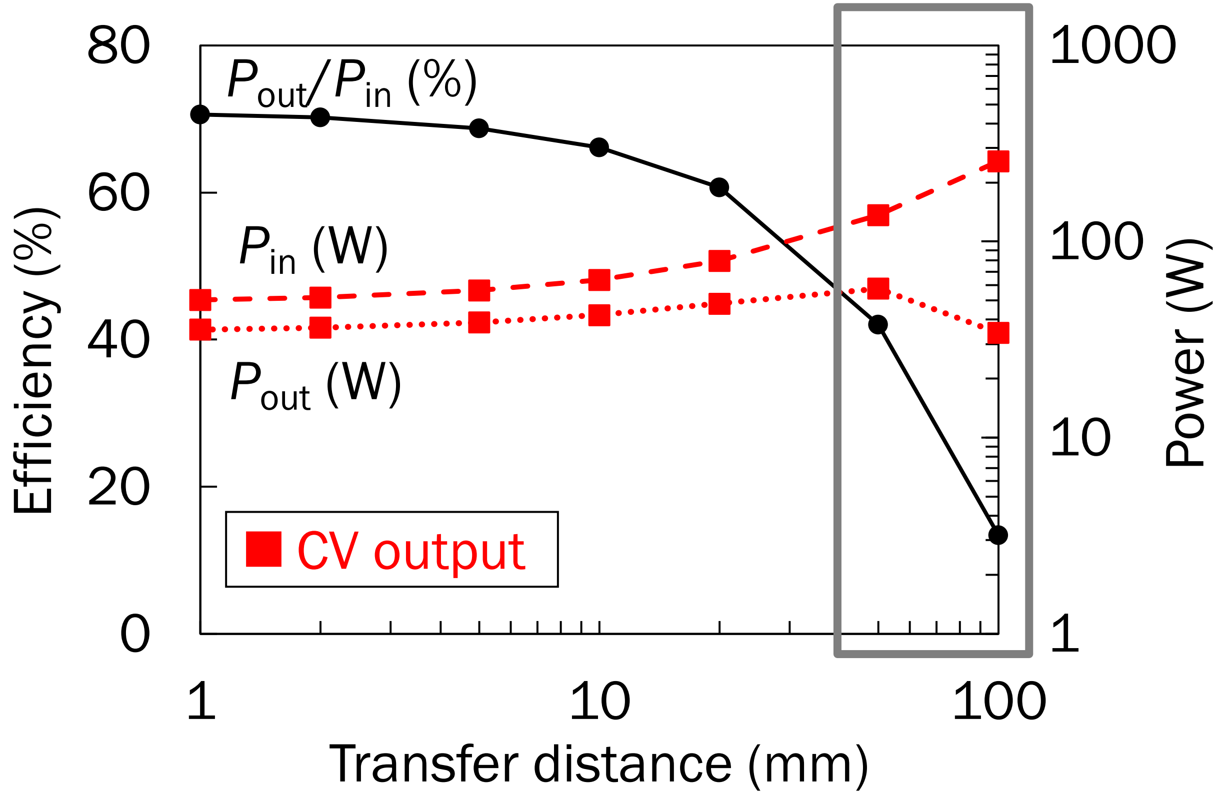


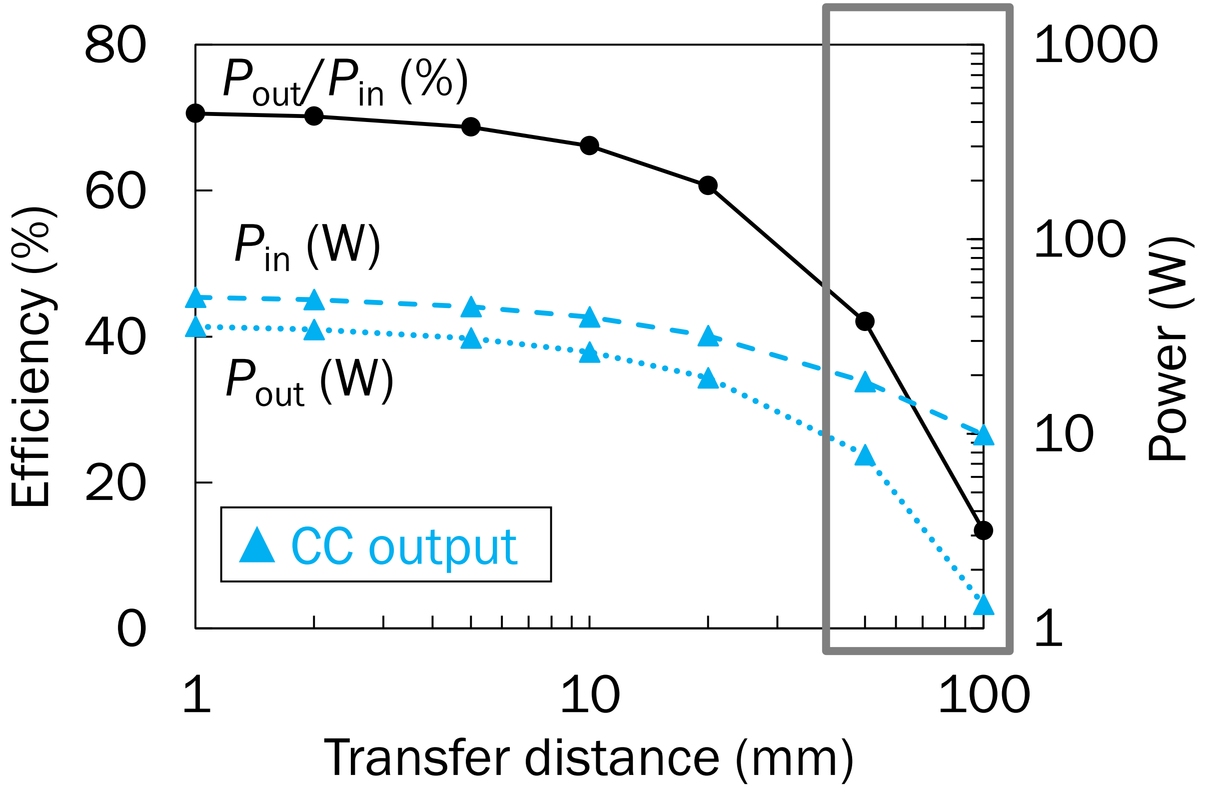
Which is suitable for the UWPT system, CV or CC operation?

Comparison of Output Operation

CV operation: Increase in P_{in} at far distances. → Large electricity waste

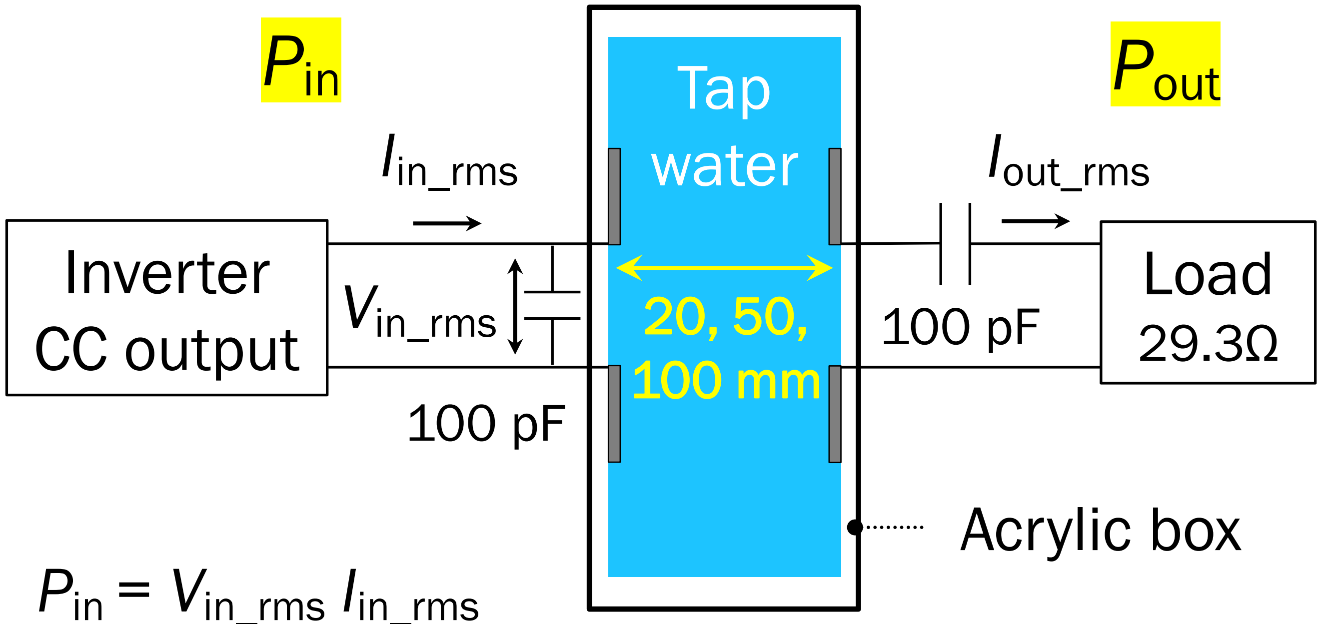
CC operation: Suppression electricity waste. → Suitable for clean energy





Demonstration Setup

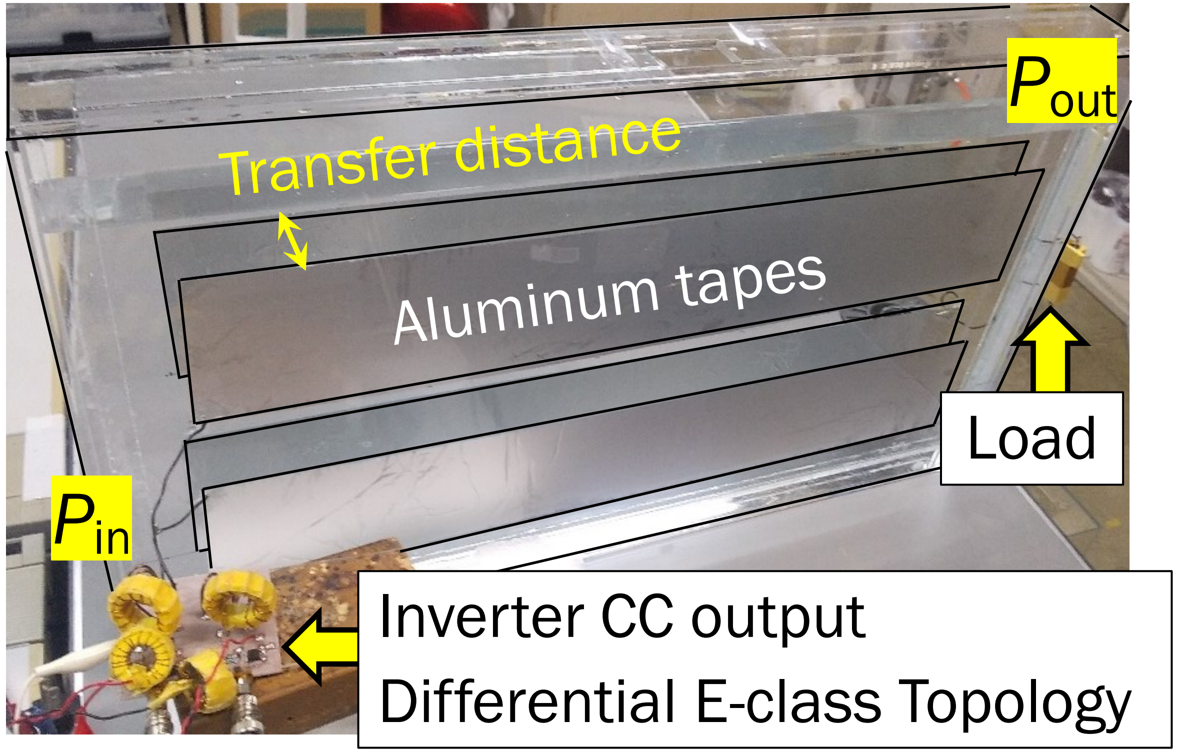
System Configuration



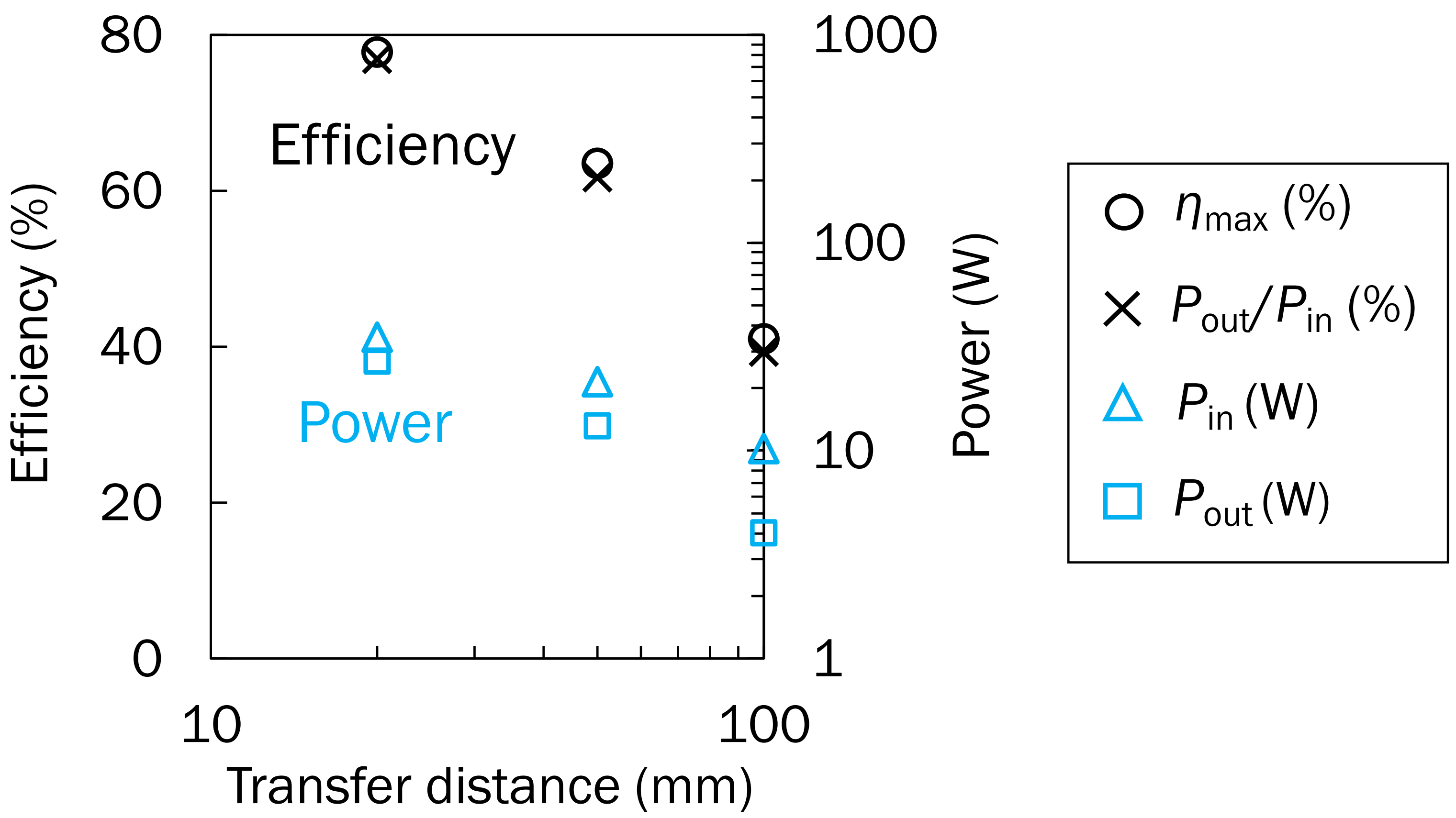
$P_{in} = V_{in\_rms} I_{in\_rms}$

$P_{out} = 29.3\, I_{out\_rms}^2$

Prototype



Experimental Result & Discussion



- P_{in} suppression at far transfer distance
- Maintenance of η_{max} at any distance

Success in demonstration of high-efficient & stable WPT system independent of transfer distance fluctuation in tap water

Comparison with Other Research

	Efficiency	Distance	Frequency	Fluctuation tolerance	Coupler size	Power
[4]	75% (RF-RF)	20 mm	27 MHz	No	750 cm^2	VNA
[5]	90% (RF-RF)	20 mm	50 MHz	No	256 cm^2	200 W
[13](1)	60% (DC-DC)	500 mm	1 MHz	No	1000 cm^2	400 W
[14]	85% (RF-RF)	5 mm	128 kHz	No	1338 cm^2	VNA
[15]	44% (RF-RF)	8 mm	839 kHz	No	1907 cm^2	47 W
This work	**79% (RF-RF)**	**20 mm**	**13.56 MHz**	**Yes**	**1525 cm^2**	**35 W**

(1) In distilled water of 0.0002 S/m. Other researches were conducted in tap water of 0.01 S/m.

[13] H. Zhang, F. Lu, *IEEE Trans. Ind. Information*, vol. 16, no. 8, pp. 5191–5201, Aug. 2020.
[14] M. Urano, A. Takahashi, *Proc. of 2016 IEEE International Meeting for Future of Electron Devices*, June 2016, pp. 1–2.
[15] H. Li, et al., *Proc. of 2022 International Conference on Power and Energy Applications*, 2022, pp. 130–137.

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Conclusion

Purpose	The straightforward and high-efficient capacitive UWPT system with fluctuation tolerance of the transfer distance
Feature	The load-independent inverter and the capacitive coupler with opposite feeding/receiving points
Result	Success in high-efficient and stable wireless power transmission independent of the distance fluctuation.
Future work	• Miniaturization of the coupler • Design of capacitive UWPT system for flowing seawater environment

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