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On a distributed parameter model for electrical impedance of ionic polymer

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K.Takagi[1,2], Y.Nakabo[3,2], Z.-W.Luo[4,2], K.Asaka[3,2]

1 Nagoya University
2 RIKEN (BMC Research Center)
3 AIST
4 Kobe University

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  - Electrical impedance of IPMC*
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  - Parameter identification
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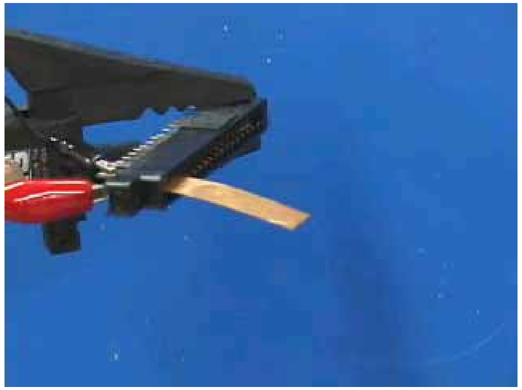


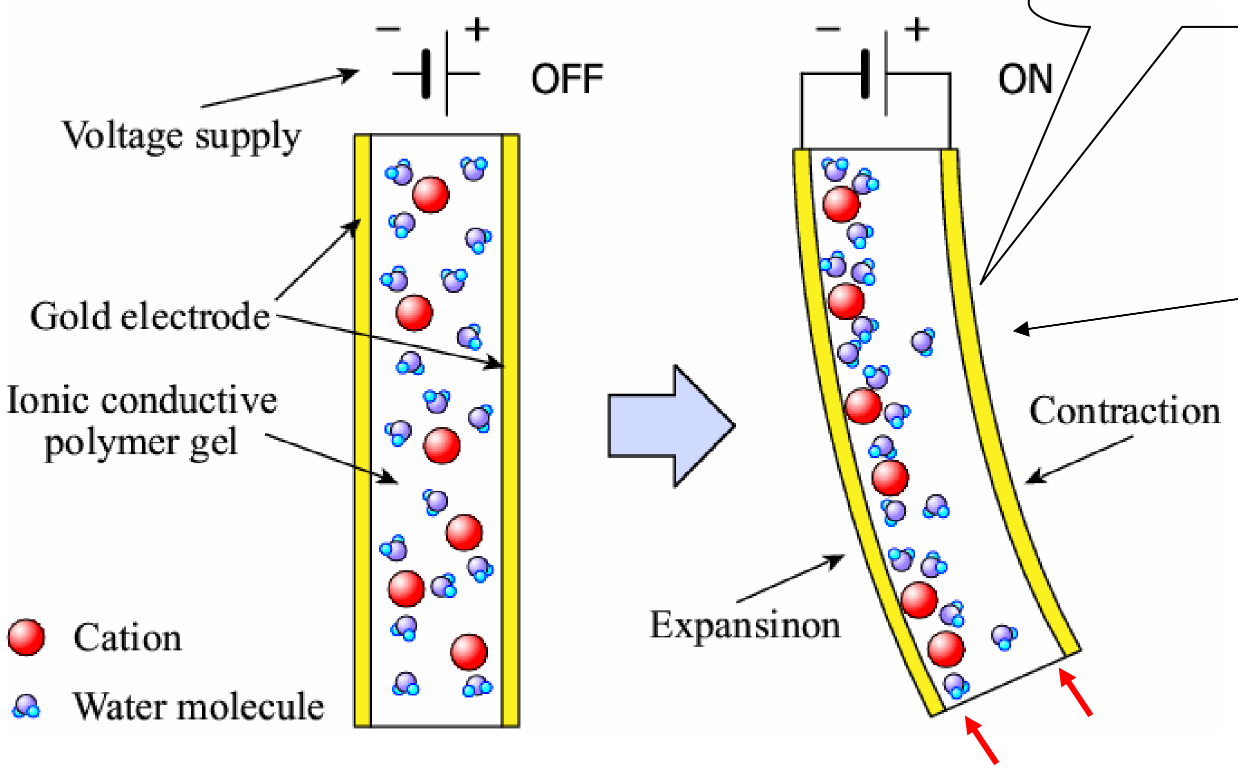
*Ionic Polymer-Metal Composite, IPMC

Introduction

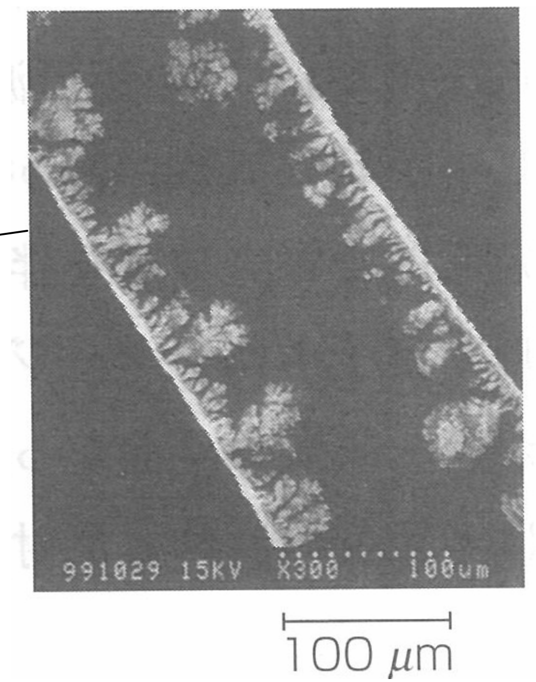
- IPMC: structure and principle

Interfacial dendrite structure

Ion transport



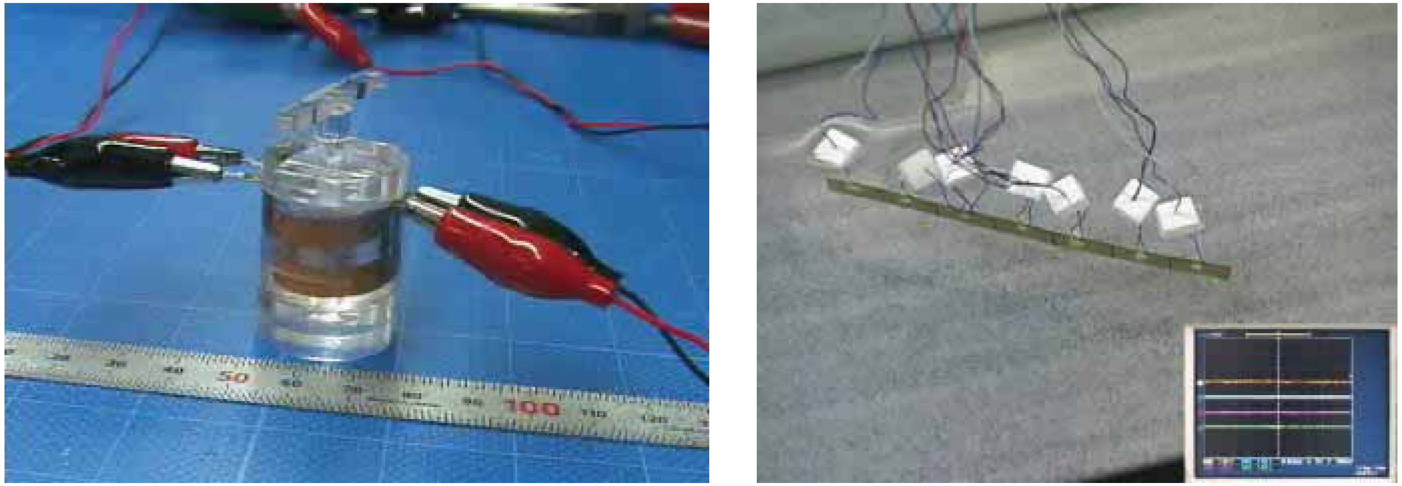
Electric double layers appear at the polymer-metal interfaces



Cross-section of an IPMC, Osada ed., Soft actuators, NTS press (2004)

Introduction

- Motivation



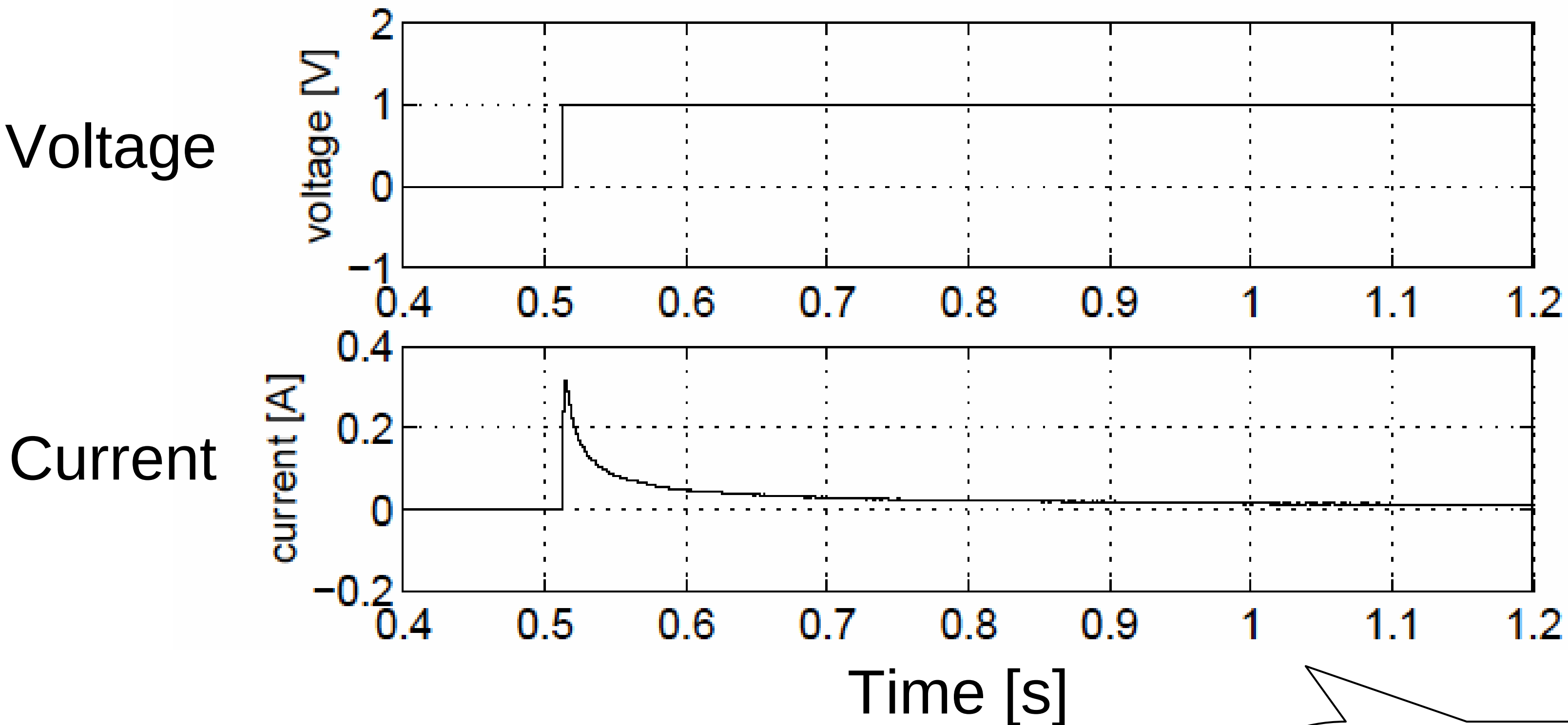
Robotic applications: a rotary actuator and a snake-like robot

IPMC requires a few volts, however it requires hundreds of milliamperes maximum.
Questions :
- Why so capacitive? (→physical modeling)
- Can we drive the IPMC more efficiently? (→designing the driver)
- Can we measure the sensor signal precisely? (→designing the instrument)

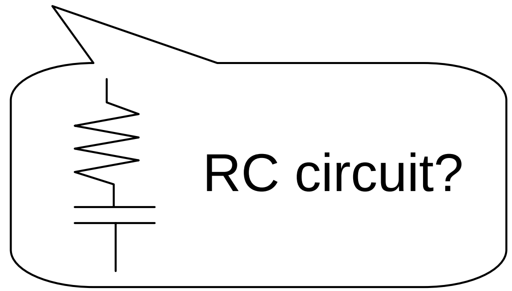
Modeling of the electrical impedance is important!

Introduction

- Electrical impedance (step response)

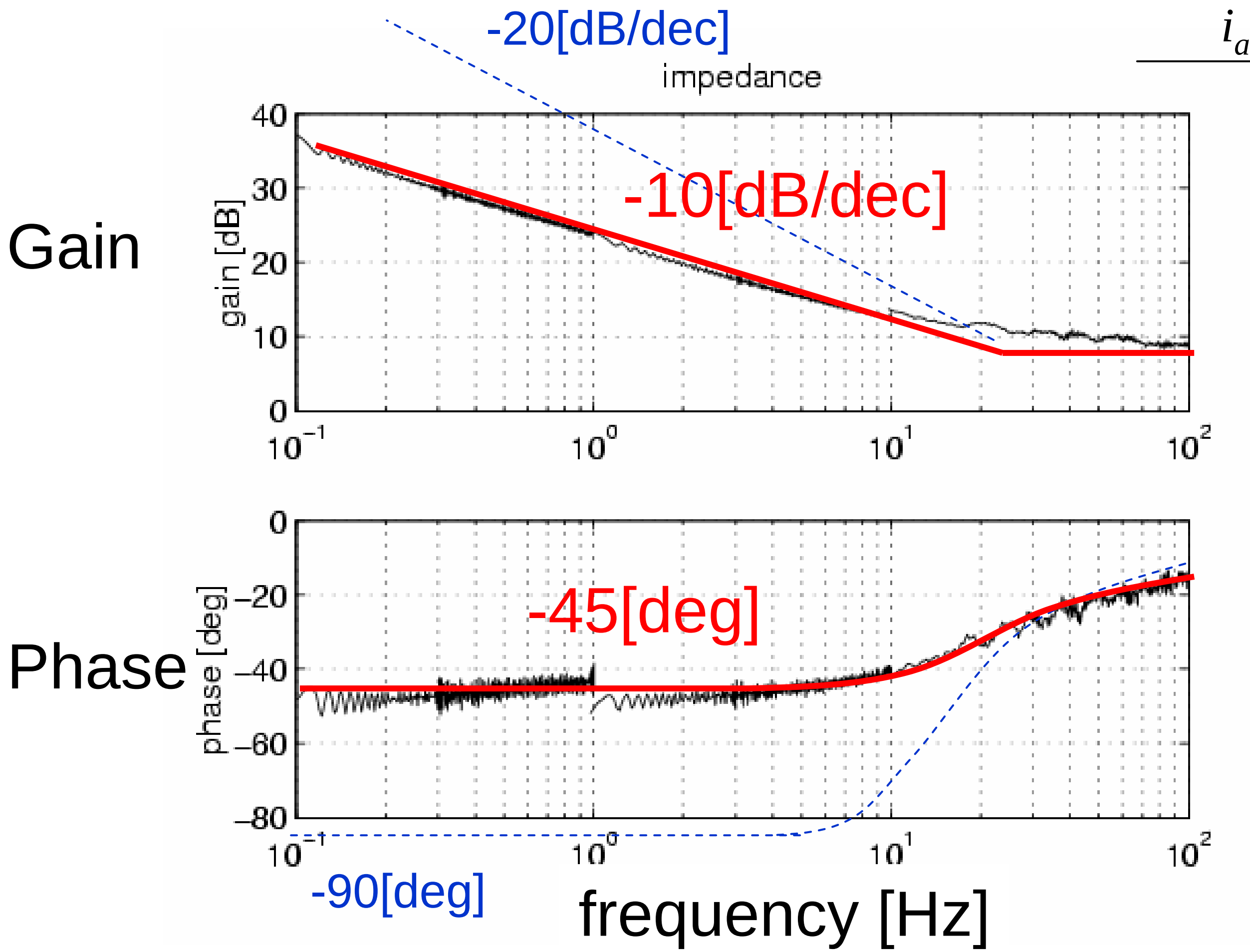


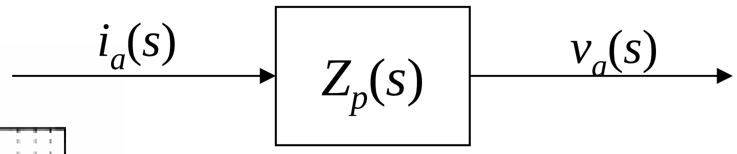
Impulse-like current flows by step voltage.
→IPMCs have (highly) capacitive impedance.



Introduction

- Electrical impedance (frequency response)





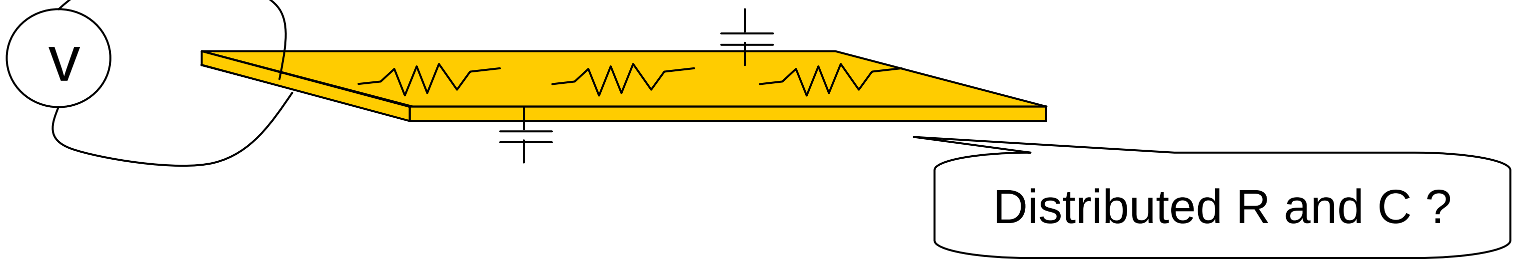
Gain/Phase property
-10[dB/dec], -45[deg]

⇒ exist of $\frac{1}{\sqrt{s}}$?

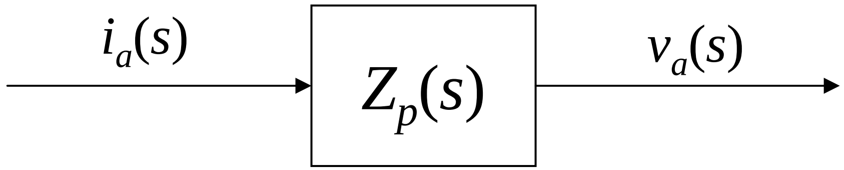
A single RC circuit
(-20[dB/dec], -90[deg])
can not describe the property

Introduction

- Objective



The Impedance of an IPMC is appropriate to be modeled as a **distributed parameter system** due to the experimental fact



Distributed parameter system modeling of the impedance and **parameter identification** from the point of view of frequency response

Models

- Physics based model
  - Transport theory
    - Farinholt and Leo, Proc. SPIE (2005)
- Circuit models
  - (Discrete) RC circuit models
    - Kanno, Tadokoro et al., Trans. JSME C (1996)
    - Newbury and Leo, J.Intell.Mater.Stuct. (2003)
  - (Continuous) RC circuit (transmission line) model
    - Bao, Bar-Cohen, Lih, Proc.SPIE (2002)

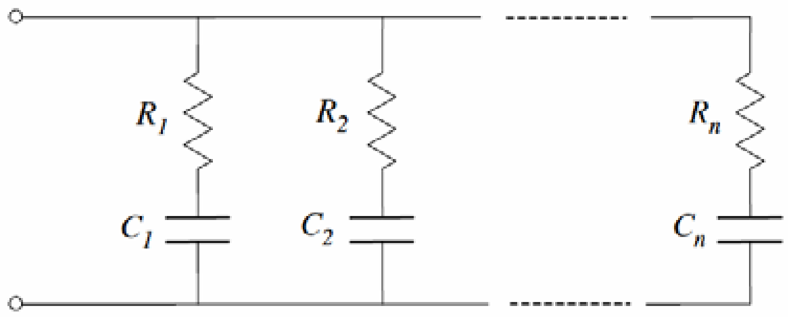


Figure 4. *Circuit model for* Z_p.

Newbury and Leo (2003)

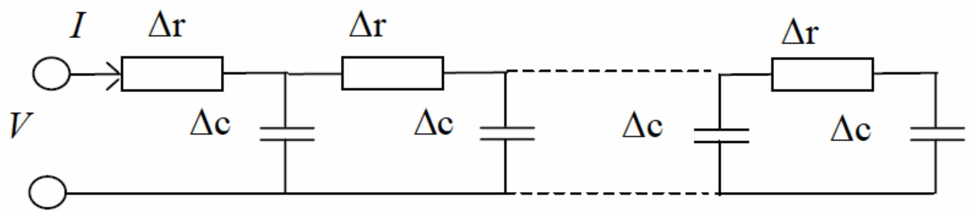


Fig. 7: Distributed RC line model for fractal-like electrode in IPMC

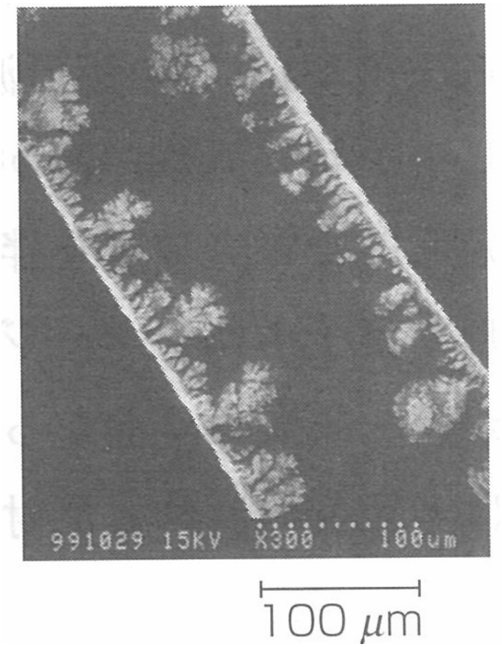
Bao, Bar-Cohen, Lih (2002)

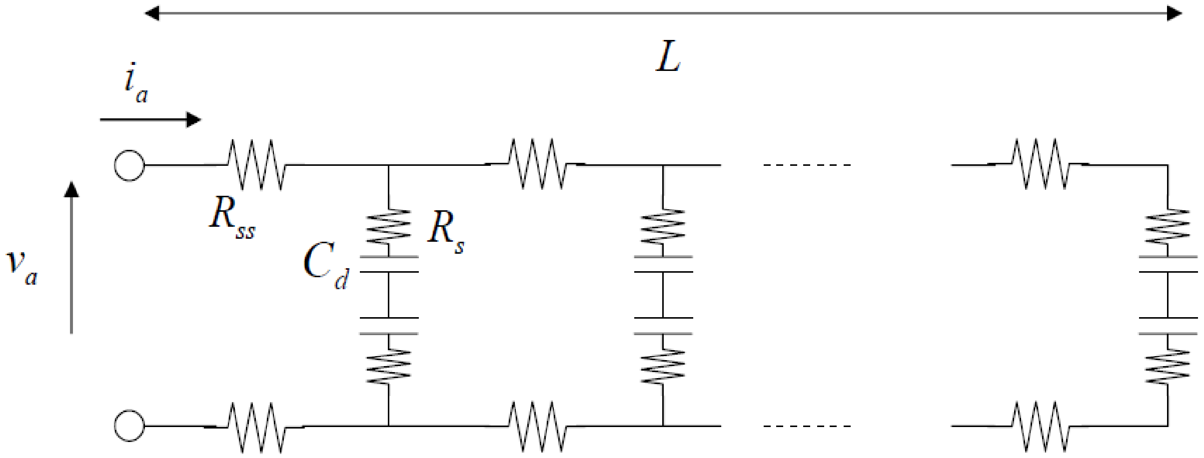
Models

- A distributed circuit model (for rough electrode)

Length parameter L[m]
Voltage and current at x=0 are V_a and I_a, respectively.

R_{ss} : Electrode resistance
R_s : Polymer resistance
C_d : Electric double layer capacitance





Uniformly distributed case

$$Z_p(s) = 2\sqrt{\frac{R_{ss}(R_s C_d s + 1)}{C_d s}} \frac{1}{\tanh\left(L\sqrt{R_{ss} C_d s/(R_s C_d s + 1)}\right)}$$

Non-uniformly distributed (parameter varying) case
→ difficult to solve…

Models

- Bode diagram of the uniformly distributed circuit

-20dB/dec
(Capacitor-like)

$$Z_p(s) \approx \frac{2}{LC_d s}$$

-10dB/dec
(Distributed RC)

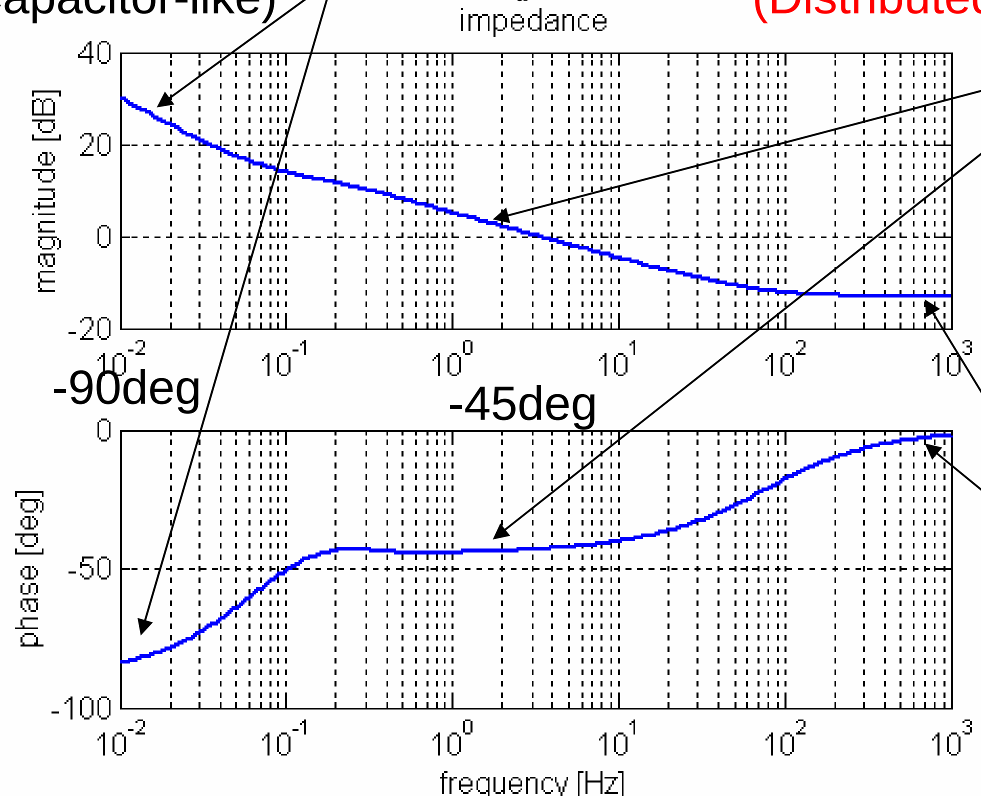
$$Z_p(s) \approx 2\sqrt{\frac{R_{ss}}{C_d s}}$$

Gain

Phase

-90deg

-45deg



constant.
(Pure resistance)

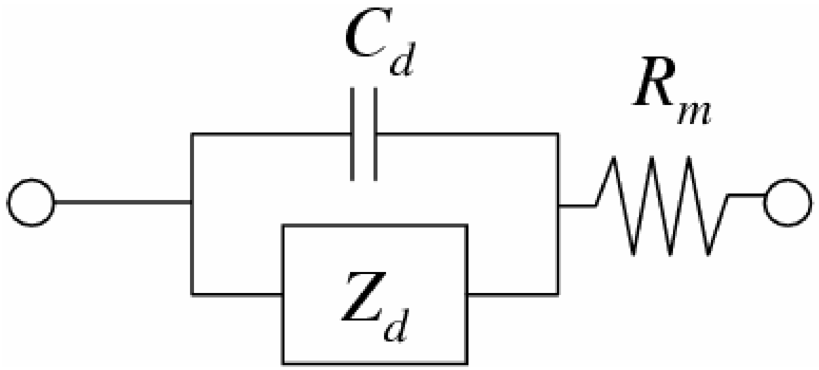
$$Z_p(s) \approx 2\sqrt{R_{ss}R_s}\frac{1}{\tanh\left(L\sqrt{R_{ss}/R_s}\right)}$$

$$Z_p(s) = 2\sqrt{\frac{R_{ss}(R_s C_d s + 1)}{C_d s}}\frac{1}{\tanh\left(L\sqrt{R_{ss}C_d s/(R_s C_d s + 1)}\right)}$$

L=0.05[m]; Rss=100[Ω/m]; Rs=1e-4[Ωm];
Cd=20[F/m];
Rp=1e7[Ωm]; Rc=0.01[Ω];

Models

- A black-box distributed circuit model



Distributed parameter system impedance

$$Z_d(s) = \frac{K_z}{\sqrt{s}}$$

K.Asaka et al.: State of Water and Ionic Conductivity of Solid Polymer Electrolyte Membranes in Relation to Polymer Actuators, J. Electroanal. Chem., 505, 24/32 (2001)

$Z_d(s)$ represents distributed properties of the DPS, not Warburg impedance.

$$Z(s) = \frac{1}{C_d s + \sqrt{s} / K_z} + R_m$$

$$-\pi / 2 < \arg(Z(j\omega)) < 0$$

$$\omega << \frac{1}{(K_z C_d)^2}, \quad Z(j\omega) \approx \frac{K_z}{\sqrt{j\omega}}$$

$$\omega >> \frac{1}{R_m C_d}, \quad Z(j\omega) \approx R_m$$

Experiment

- Method: parameter identification

Frequency domain least squares method

model — data

$$\hat{p} = \arg\min_{p} \sum_{k} \left| W(\mathrm{j}\omega_k)\left(Z(\mathrm{j}\omega_k; p) - z_k\right)\right|^2$$

where p is a parameter vector $p := [C_d, R_m, K_z]$

$$Z(s) = \frac{1}{C_d s + \sqrt{s} / K_z} + R_m$$

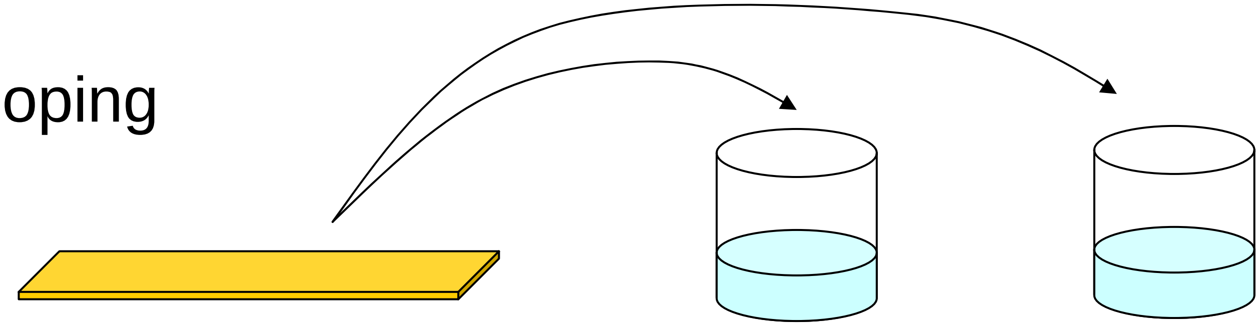
The cost function is minimized by the numerical optimization technique (using MATLAB Optimization Toolbox)

Experiment

- Method：impedance measurement

45[mm]x5[mm] Nafion N-117 (5 times gold plated)
Impedance measurement using an impedance analyzer (va=0.3V)

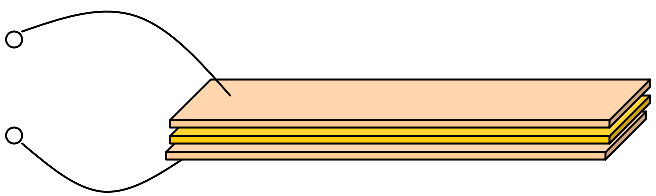
(1) Ion doping



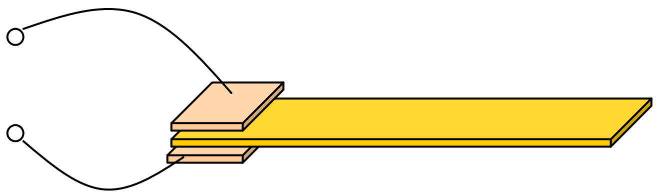
(a) 0.1mol/l NaOH　　(b)0.2mol/l TEA-Cl*

(2) Clamp method

*TEA(Tetraethylammonium)



(a) Fully clamped



(b) Partially clamped

Experiment

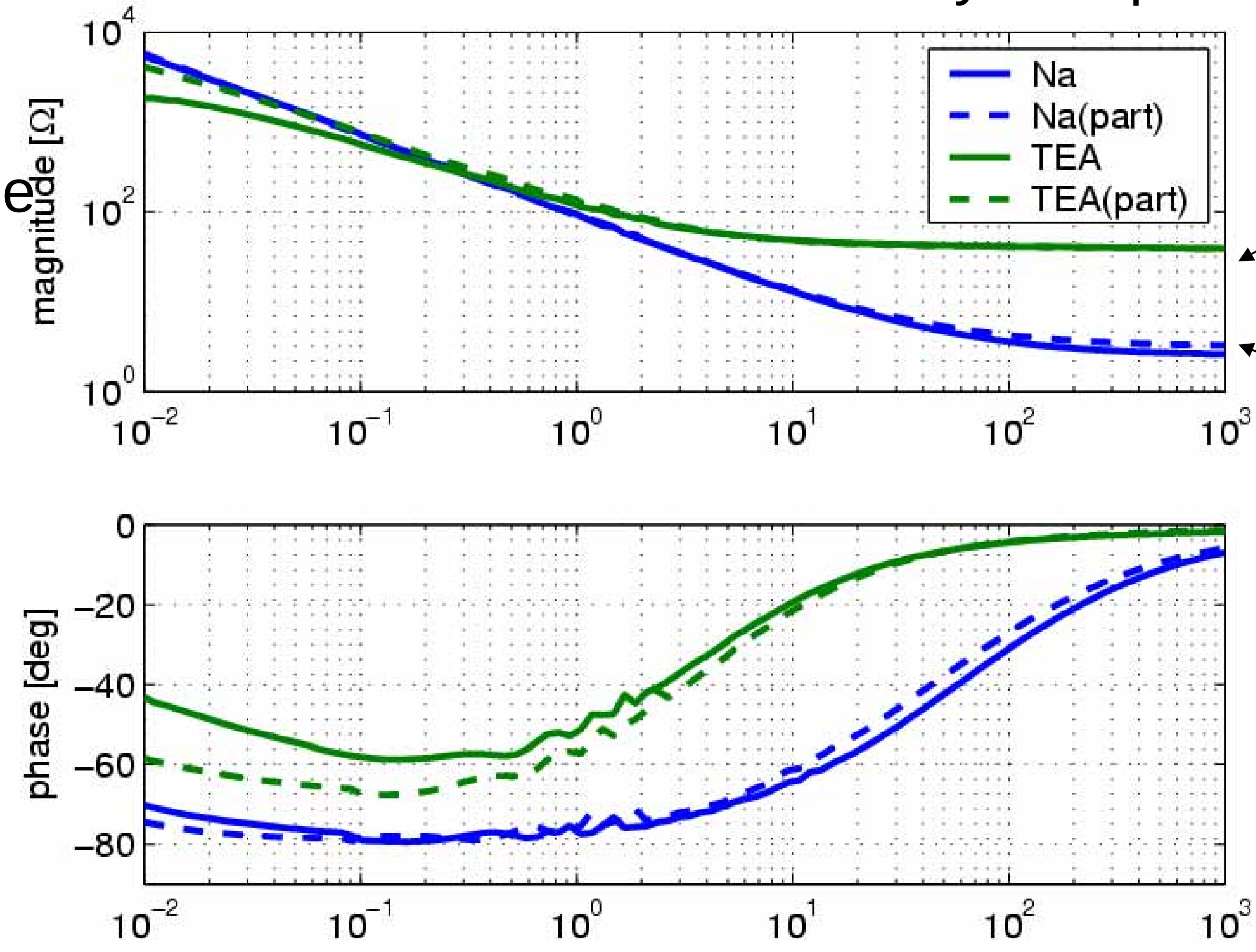
- Results

Solid ：Fully clamped
Dashed ：Partially clamped

Magnitude [Ω]

TEA case

Na case



Phase [deg]

Frequency [Hz]

Experiment

- Discussion

For Au-plated Nafion,

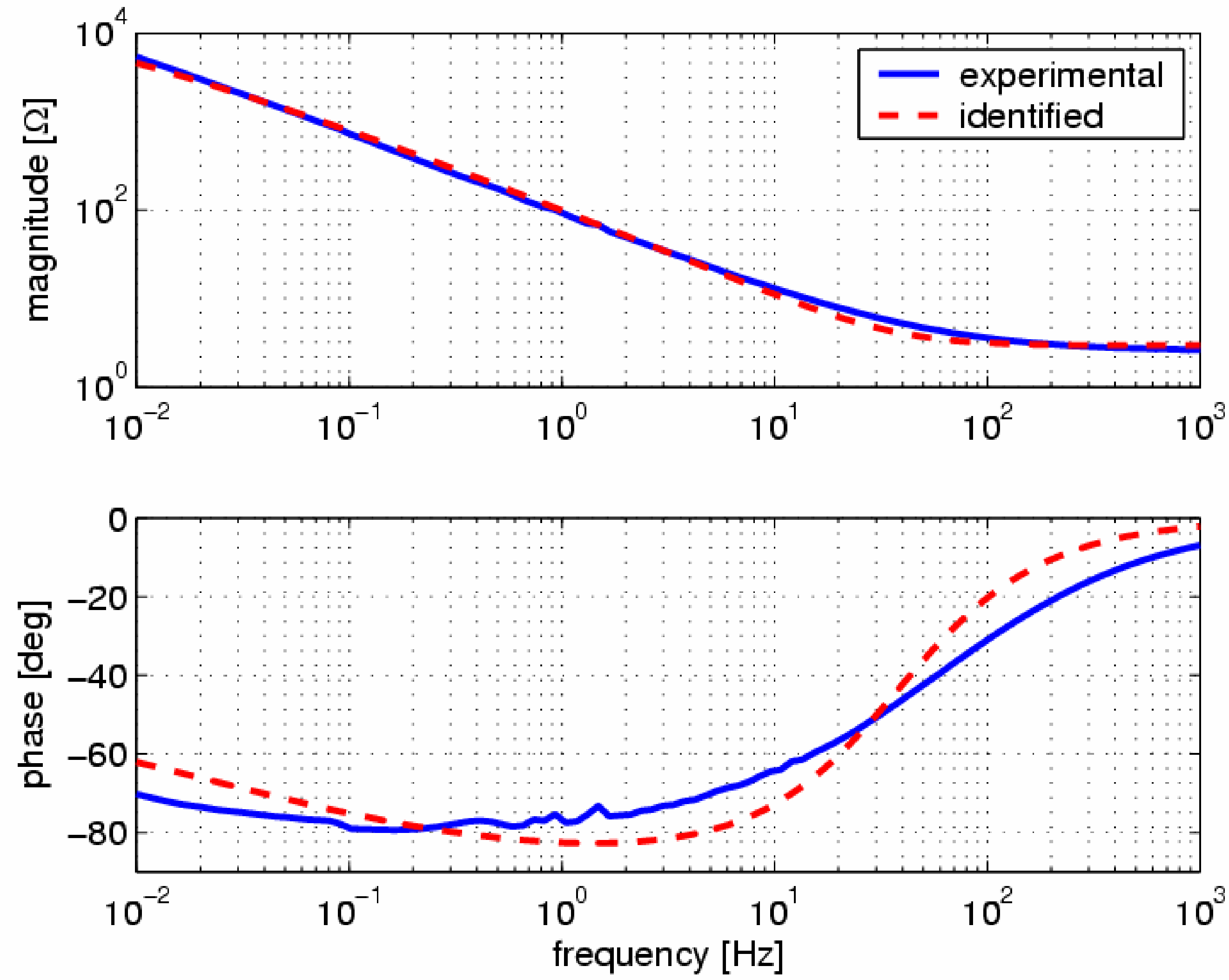
- The impedance varies by ion species.
- The impedance does not vary by clamp method?

→ The counter ion species affect the impedance.

→ Surface electrode resistance is small?
→ The resistance is for the polymer-metal interface?

Experiment

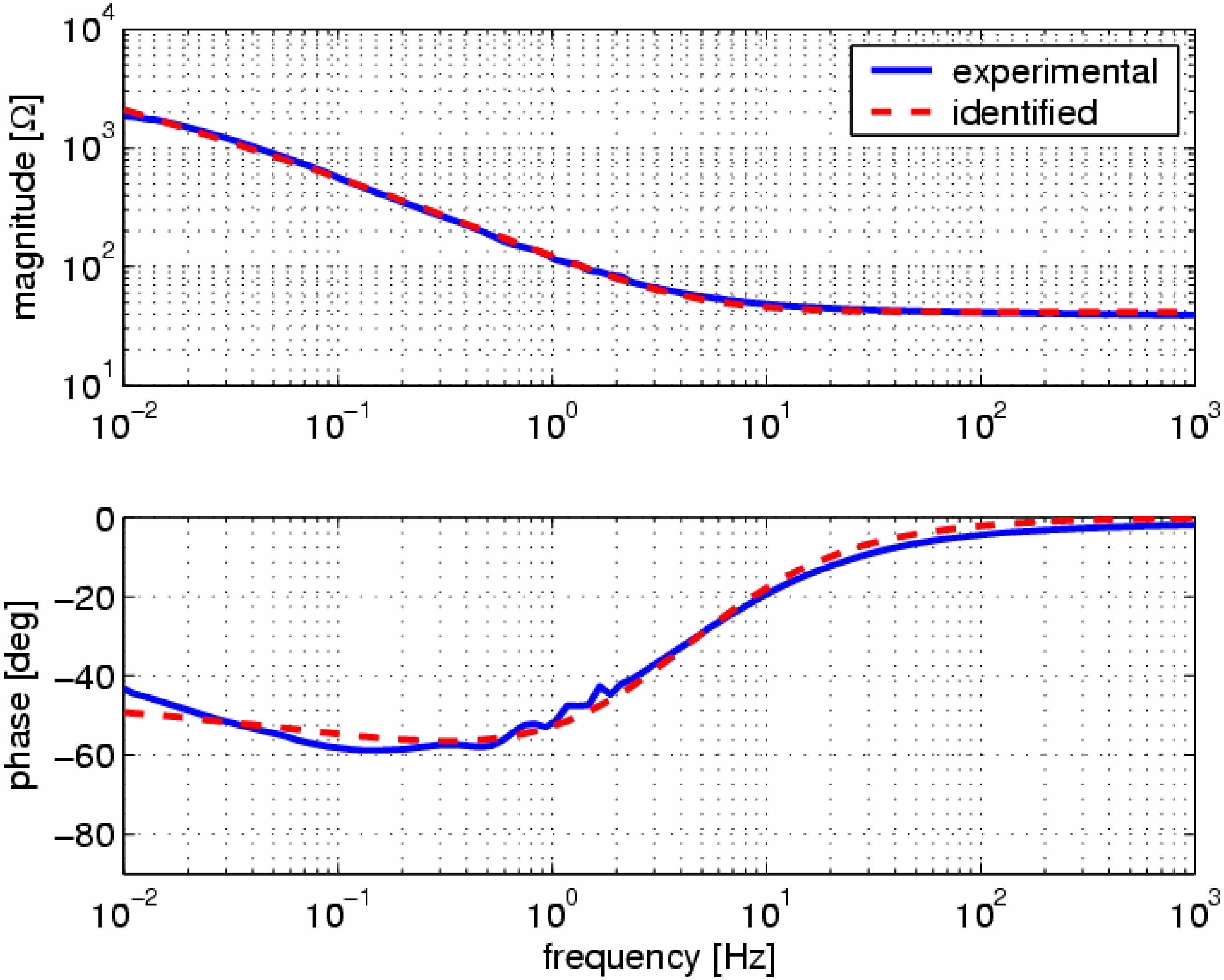
- Parameter identification: Na ion case



Experimental data
Identified model

Experiment

- Parameter identification: TEA ion case



Experimental data
Identified model

Experiment

- Results

$$Z(s) = \frac{1}{C_d s + \sqrt{s} / K_z} + R_m$$

Cation	$R_m\,[\Omega]$	C_d [F]	K_z [$F^{-1}\ s^{1/2}$]
Na^+	2.938	1.4367×10^{-3}	1750.7
TEA^+	41.544	0.9610×10^{-3}	574.0

In the case of the larger ion (TEA>Na),

- Membrane resistance R_m **increases**
- Capacitance C_d **decreases**
- Parameter $1/K_z$ **increases**

(⇒ the distributed system property **increases**)

Conclusion

- Electrical impedance measurement
  - Clamp conditions
  - Counter ion species
- Distributed circuit models
  - An uniformly distributed case
  - A black-box model
- Future works
  - Non-uniformly distributed case
  - Physics based modeling
  - Applications utilizing the model

Thank you for your attentions!