Directivity Control Using Two Circular Loudspeaker Arrays

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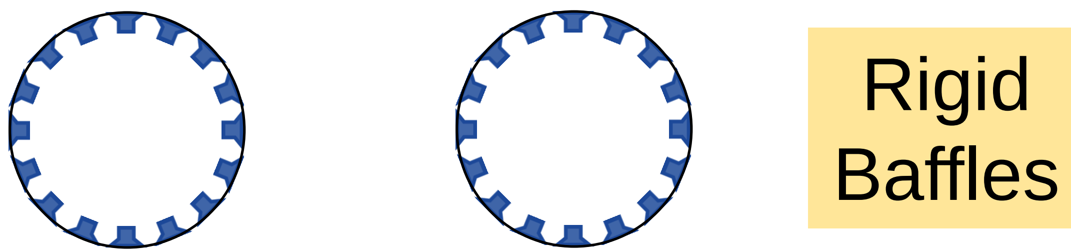
Introduction

- Two Circular Loudspeaker Arrays (2CLA)



  - Our previous work: sound field reproduction using 2CLA
- Performance of 2CLA in directivity control
  - Comparing with linear loudspeaker arrays (LLA) and single circular loudspeaker arrays (CLA)

Our Previous Works

Yi Ren, Yoichi Haneda, "Virtual Source Reproduction Using Two Rigid Circular Loudspeaker Arrays", in Proc. Audio Engineering Society 145th International Convention, Oct. 2018.

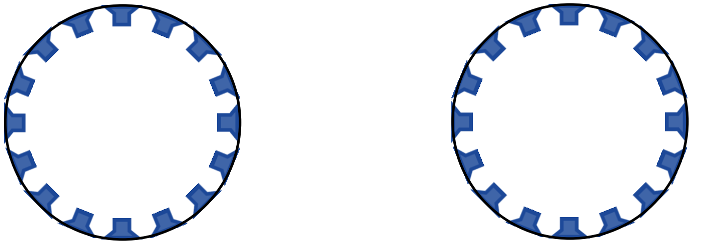
- Transfer function of 2CLA
- Sound Field Reproduction using 2CLA

Conclusion:

2CLA have the potential to get a better performance in sound field reproduction than CLA

Introduction

- Two Circular Loudspeaker Arrays



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Directivity Control

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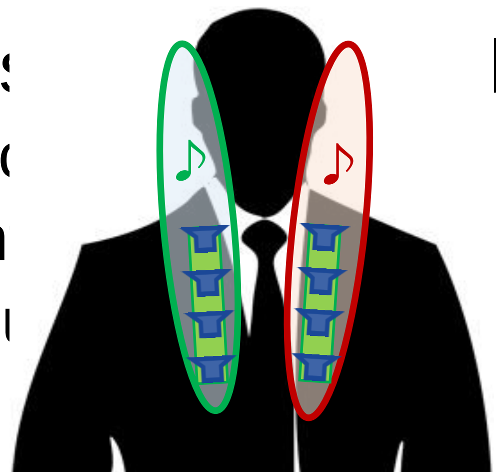

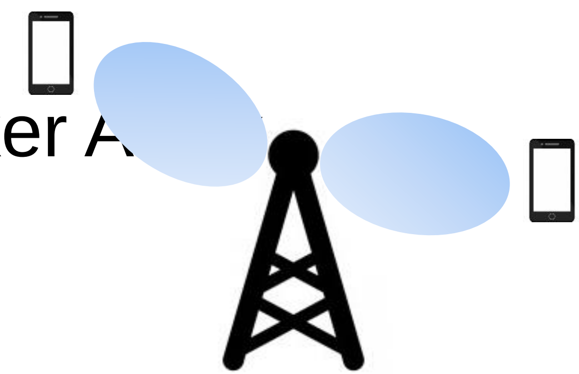

- Ap ation with L udspeaker A
  - P al Aud
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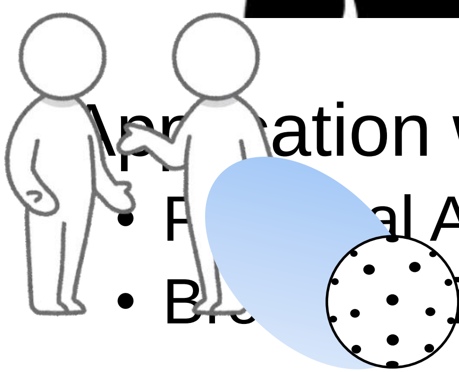
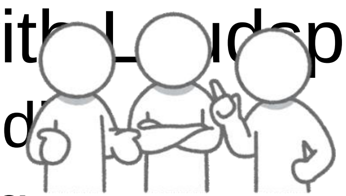
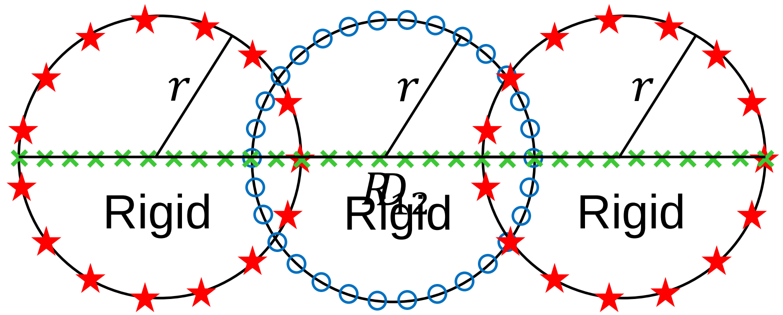




Loudspeaker Arrays

- Number of loudspeakers: $L = 30$
- 2CLA ★
  - Radii: $r_{0,(1)} = r_{0,(2)} = r = 0.15\ \mathrm{m}$
  - Distance between centers: $R_{12} = 0.5\ \mathrm{m}$



- CLA ○
  - Radius: $r_0 = r = 0.15\ \mathrm{m}$
  - Maximum order: $N = 14$
- LLA (Uniform) ×
  - Maximum distance: $D = 0.8\ \mathrm{m}$
  - Interval: $\Delta d = 2.76\ \mathrm{cm}$ ($f_{Nyq} = \frac{c}{2\Delta d} = 6.1\ \mathrm{kHz}$)

Least Square Method

Control the directivity (as sound pressure) on a circle:

$$P(r,\phi,\omega) = \sum_{l=1}^{L} \boxed{G(r,\phi|r_l,\phi_l,\omega)} w_l(\omega)$$

G: Transfer Function
w_l: Filter

Then the filter: (target directivity as $\mathbf{d}$)

$$\mathbf{w} = \mathbf{G}^{-1}\mathbf{d}$$

- CLA (open array):

$$G_{\mathrm{CLA}}(\boldsymbol{r}|\boldsymbol{r}_l) = -\frac{j}{4} H_0^{(2)}(k|\boldsymbol{r}-\boldsymbol{r}_l|)$$

- CLA (rigid array):

- 2CLA:

$$G_{\mathrm{2CLA}}(\boldsymbol{r}|\boldsymbol{r}_l) = \begin{cases} \left(\boldsymbol{\psi}_{(1)}^{\mathrm{T}} + \boldsymbol{\psi}_{(2)}^{\mathrm{T}}\mathbf{T}_{(21)} + \cdots\right)\boldsymbol{\gamma}_{(1)}, & 0 < l \le L_1 \\ \left(\boldsymbol{\psi}_{(2)}^{\mathrm{T}} + \boldsymbol{\psi}_{(1)}^{\mathrm{T}}\mathbf{T}_{(12)} + \cdots\right)\boldsymbol{\gamma}_{(2)}, & L_1 < l \le L \end{cases}$$

Least Square Method

Filter Gain

$$W_0 = 10\log_{10}\|\mathbf{w}\|_2^2$$

- Output level of loudspeakers
- Huge Gain -> Distortion / Damages

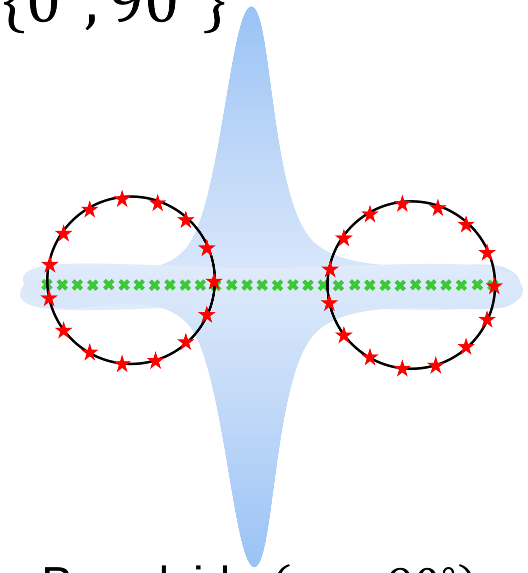
To control the filter gain at the same time:

$$\mathbf{w} = \frac{\mathbf{G}^{\mathrm{H}}\mathbf{d}}{\mathbf{G}^{\mathrm{H}}\mathbf{G} + \lambda\mathbf{I}}$$

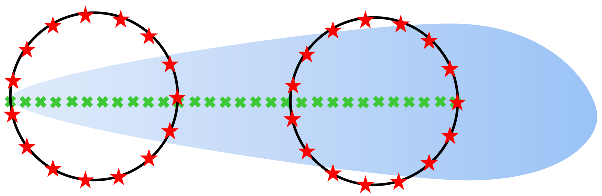
: L2-norm regularization

Experiment

- Number of control points: 48 (25 for LLA)
- $D(\phi) = \delta(\phi - \varphi)$, $\phi \in [0,2\pi)$ ($\phi \in [0, \pi]$ for LLA)
- Filter Gain: $W_0 = 0\ \mathrm{dB}$
- $\varphi \in \{0°, 90°\}$



Broadside ($\varphi = 90°$)



Endfire ($\varphi = 0°$)

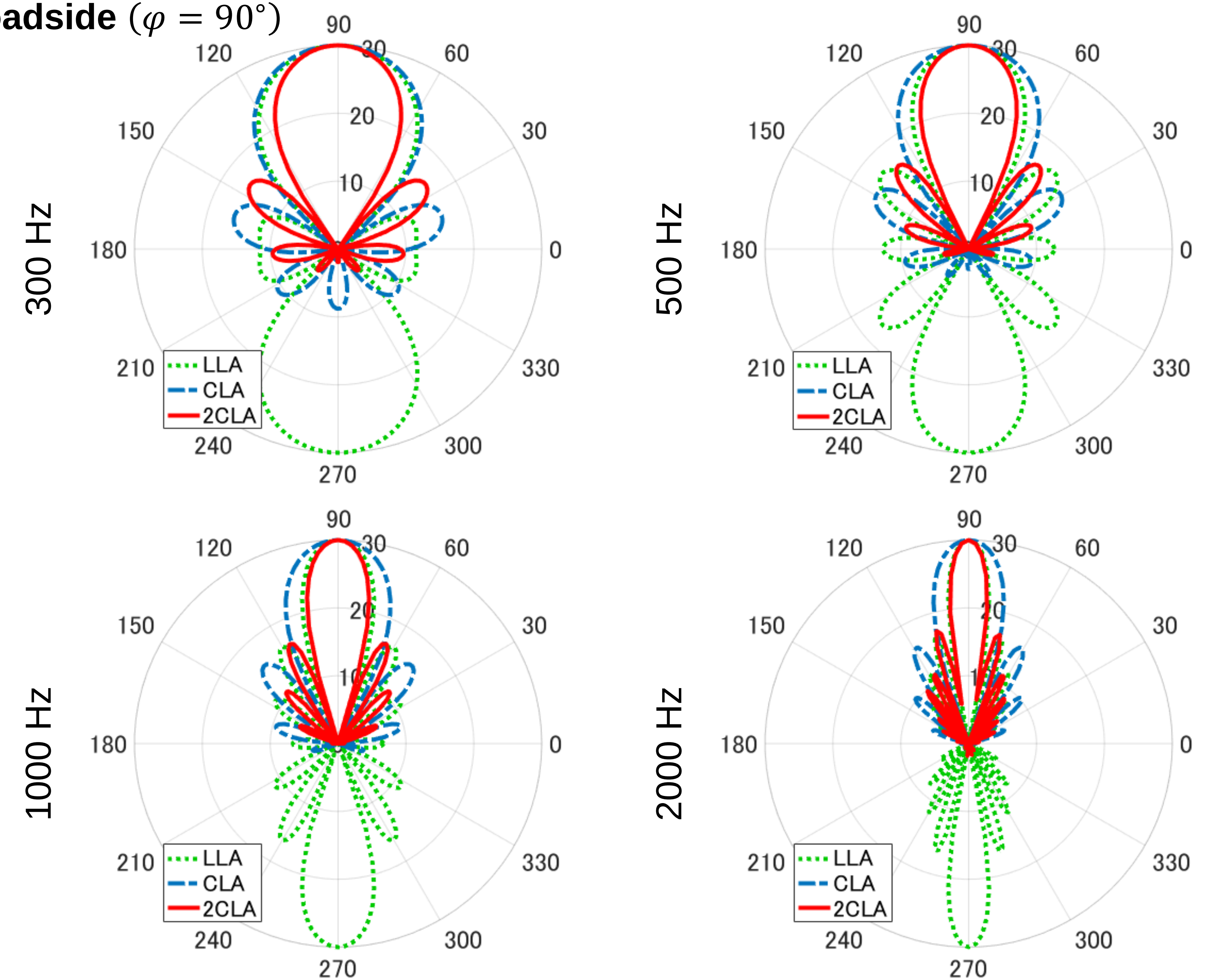
Performances

- Directivity Patterns
  - Normalized to maximum of 30 dB
- Directivity Index (DI)

$$\mathrm{DI} = 10\log_{10}\frac{2\pi\left\|P_{\varphi}\right\|^2}{\int_0^{2\pi}\left\|P_{\phi}\right\|^2 d\phi}$$

  - The power of the look direction
- Beam Width (BW)
  - Half power ($-3\ \mathrm{dB}$) beam width of the main lobe
  - The narrowness of the main beam
- Side Lobe Level (SLL)
  - The maximum level of the side lobe
  - Relative to the main lobe

Broadside $(\varphi = 90^\circ)$

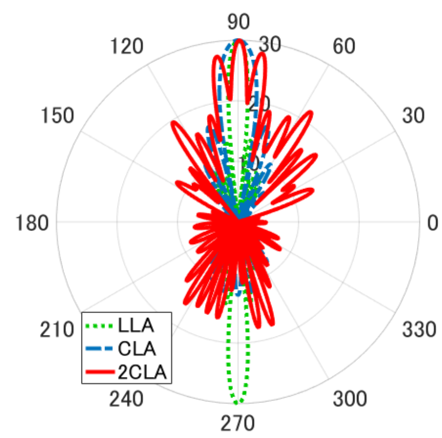


Results: Broadside

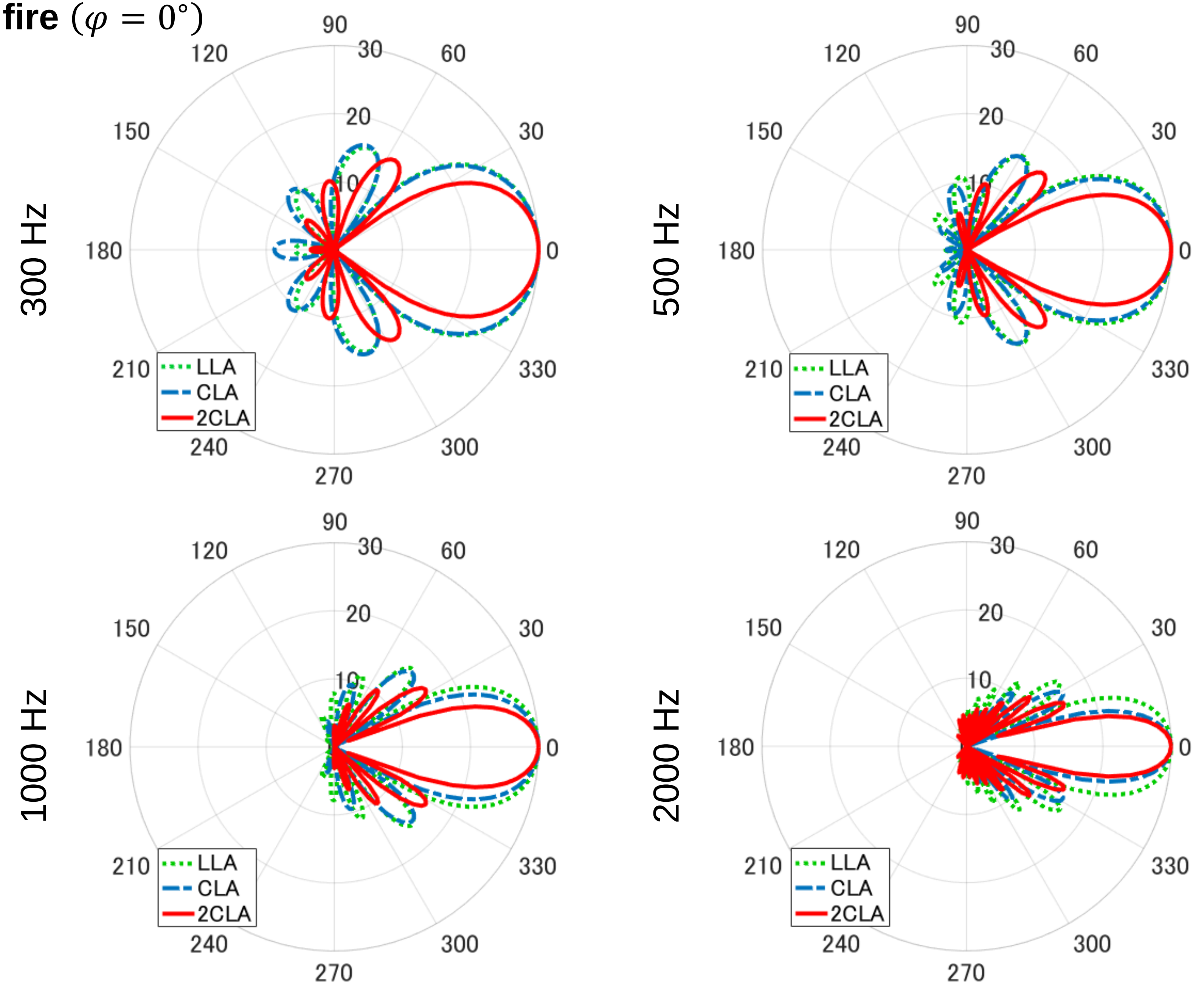
		LLA			CLA			2CLA		
Fs	φ	DI	BW	SLL	DI	BW	SLL	DI	BW	SLL
300	90	6.2	40	0	8.7	44	-14.0	10.1	32	-14.0
1000	90	9.5	18	0	11.0	26	-14.2	13.2	15	-13.6
2000	90	12.0	10	0	12.7	17	-13.9	15.3	9	-12.6
5000	90	14.8	5	0	14.8	10	-13.5	13.8	3	-1.9

*DI, SLL in dB, BW in degrees

Directivity Patterns in higher frequency:
(5000 Hz)



Endfire $(\varphi = 0°)$

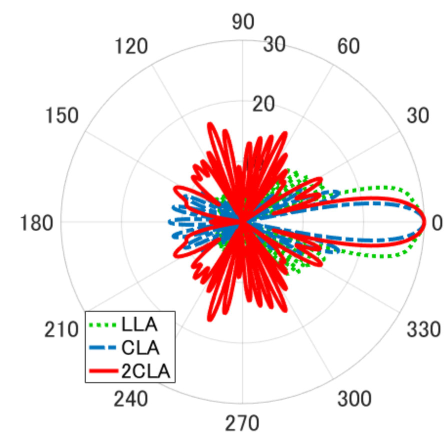


Results: Endfire

		LLA			CLA			2CLA		
Fs	φ	DI	BW	SLL	DI	BW	SLL	DI	BW	SLL
300	0	8.7	45	-14.2	8.7	44	-14.0	9.8	34	-14.1
1000	0	10.3	31	-13.8	11.0	26	-14.2	12.1	20	-14.1
2000	0	11.2	25	-13.4	12.7	17	-13.9	13.4	15	-14.3
5000	0	12.4	21	-15.2	14.8	10	-13.5	13.1	13	-12.8

*DI, SLL in dB, BW in degrees

Directivity Patterns in higher frequency:
(5000 Hz)



Discussion

- 2CLA
  - High performance at low frequencies
  - Some troubles at higher frequencies
  - Slightly better DI & BW at $\varphi = 90°$

- vs CLA (under 2000 Hz)
  - Narrower main lobe
  - Close side lobe level

- vs LLA (under 2000 Hz)
  - Narrower main lobe (especially at $\varphi = 0°$)
  - More robust to look directions

Conclusion

- The 2CLA model is possible to be applied for directivity control.
- 2CLA can produce a higher directivity beam than LLA or CLA at low frequencies.
- 2CLA is robust with respect to directions.

Future Works

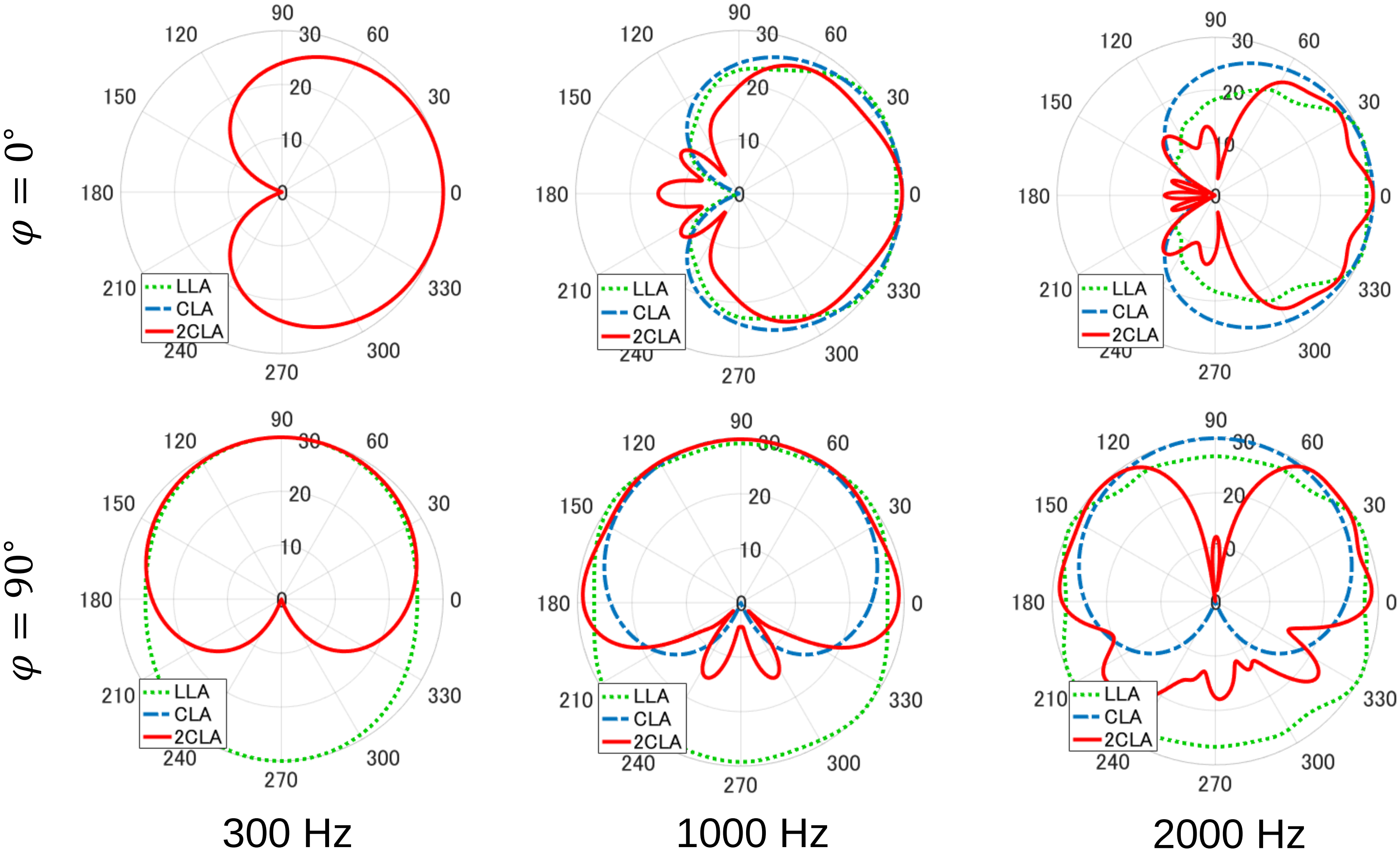
- How does the distance and radius of the 2CLA affect the performance.
- More details about the high frequencies and other beam patterns

Thanks For Listening

Q & A

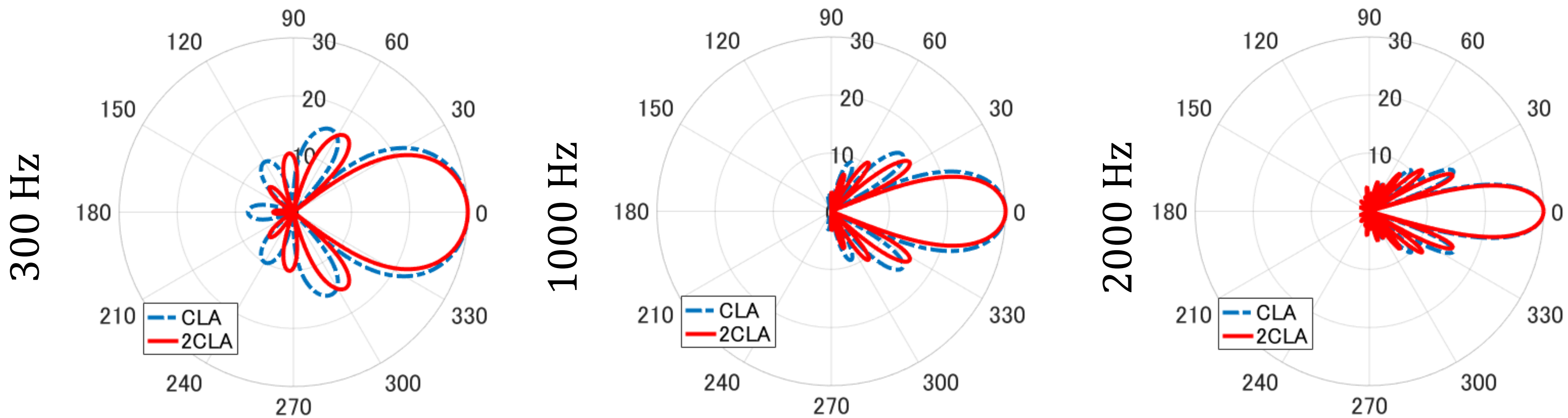
Appendix: Another Directivity

- $D(\phi) = \cos(\phi - \varphi),\ \phi \in [0, 2\pi)$



Appendix: Another CLA

Center at $(0.25\ \mathrm{m}, 0\ \mathrm{m})$



		CLA			2CLA		
Fs	φ	DI	BW	SLL	DI	BW	SLL
300	0	9.3	38	-14.4	9.8	34	-14.1
1000	0	11.5	23	-14.4	12.1	20	-14.1
2000	0	13.2	15	-14.0	13.4	15	-14.3

Appendix: Prototype