Multi-Electrode Approach for Interfacing Optical Computing Devices

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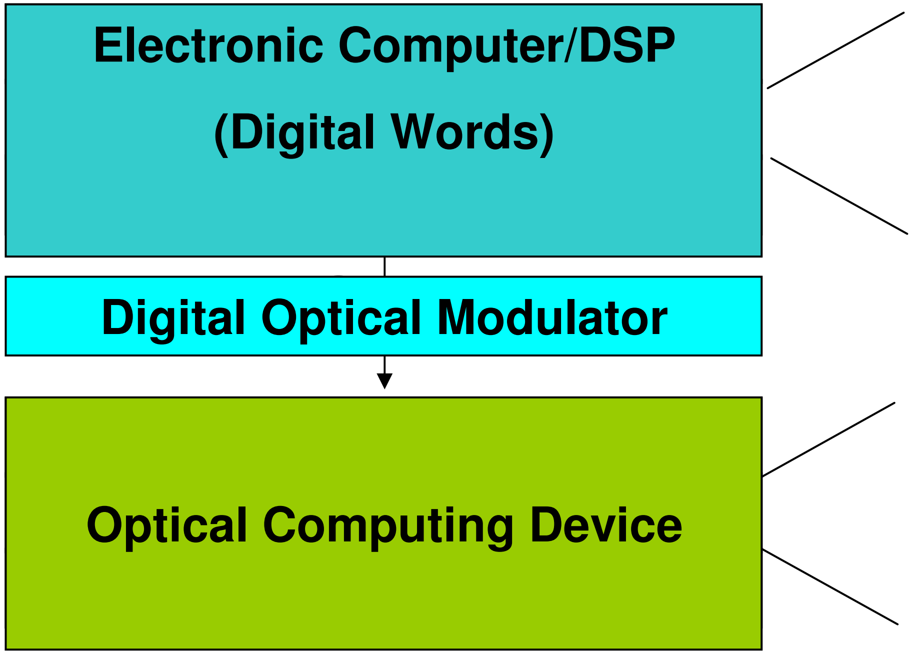
Outline

- Motivation
- The Interfacing Problem
- Multi-Electrode Intensity Optical Digital Modulator
- Optical IQ Modulator
- Conclusions

Motivation

- Future optical computing devices will have to interface to electronic systems.
- ‘’Casting’’ of digital signals on optical waveforms requires complex analog conversion circuits.

The Interfacing Problem

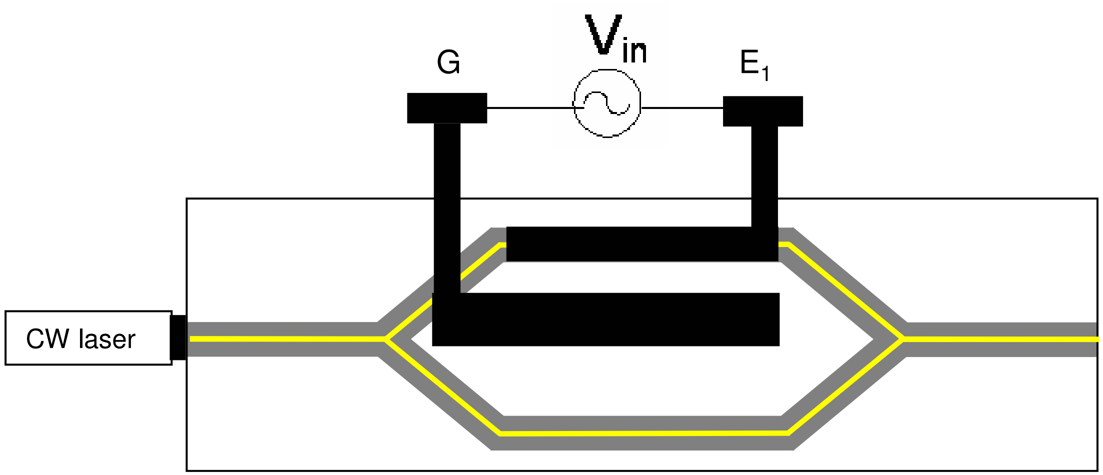


- Digital Electronics
- Binary Logic

- Intensity and Phase
- Analog Optical Computing
- Multi-Level Logic -

- *Raymond Arrathoon "Optical Computing, Digital and Symbolic"*

Integrated optical intensity modulator based on a MZM

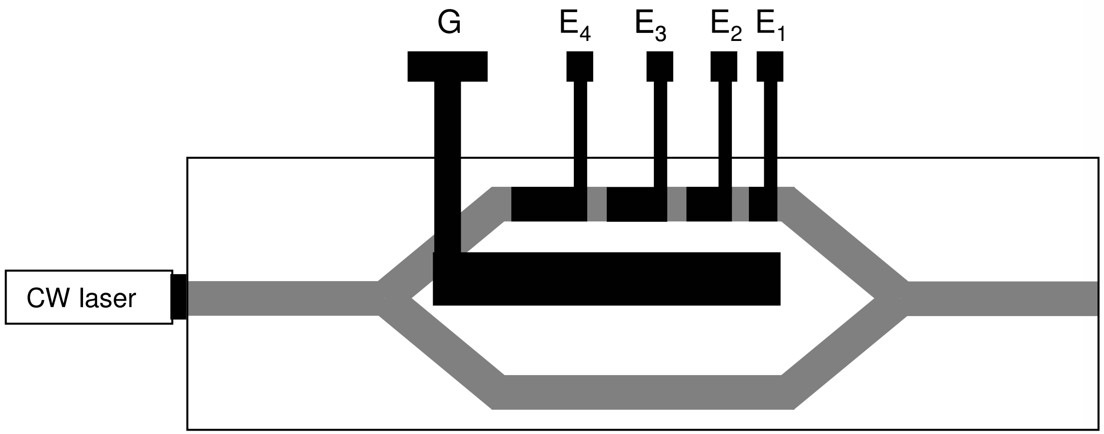


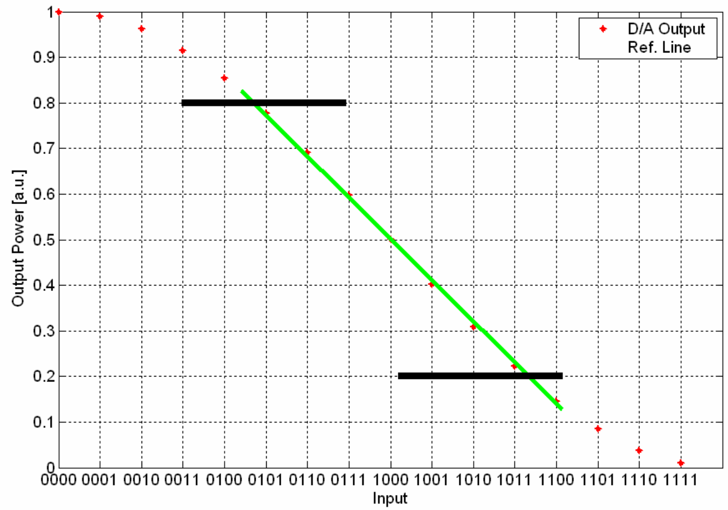
•Intensity Transmission

$$T = \cos^2\left(\frac{\pi}{2}\frac{V_{in}}{V_\pi}\right)$$

Optical Digital Modulator using Multi-Electrode MZM

- M. Papuchon, C. Puech, and A. Schnapper, "4-bits digitally driven integrated amplitude modulator for data processing," *Electronics Letters*, vol. 16, pp. 142–144, Feb. 1980.

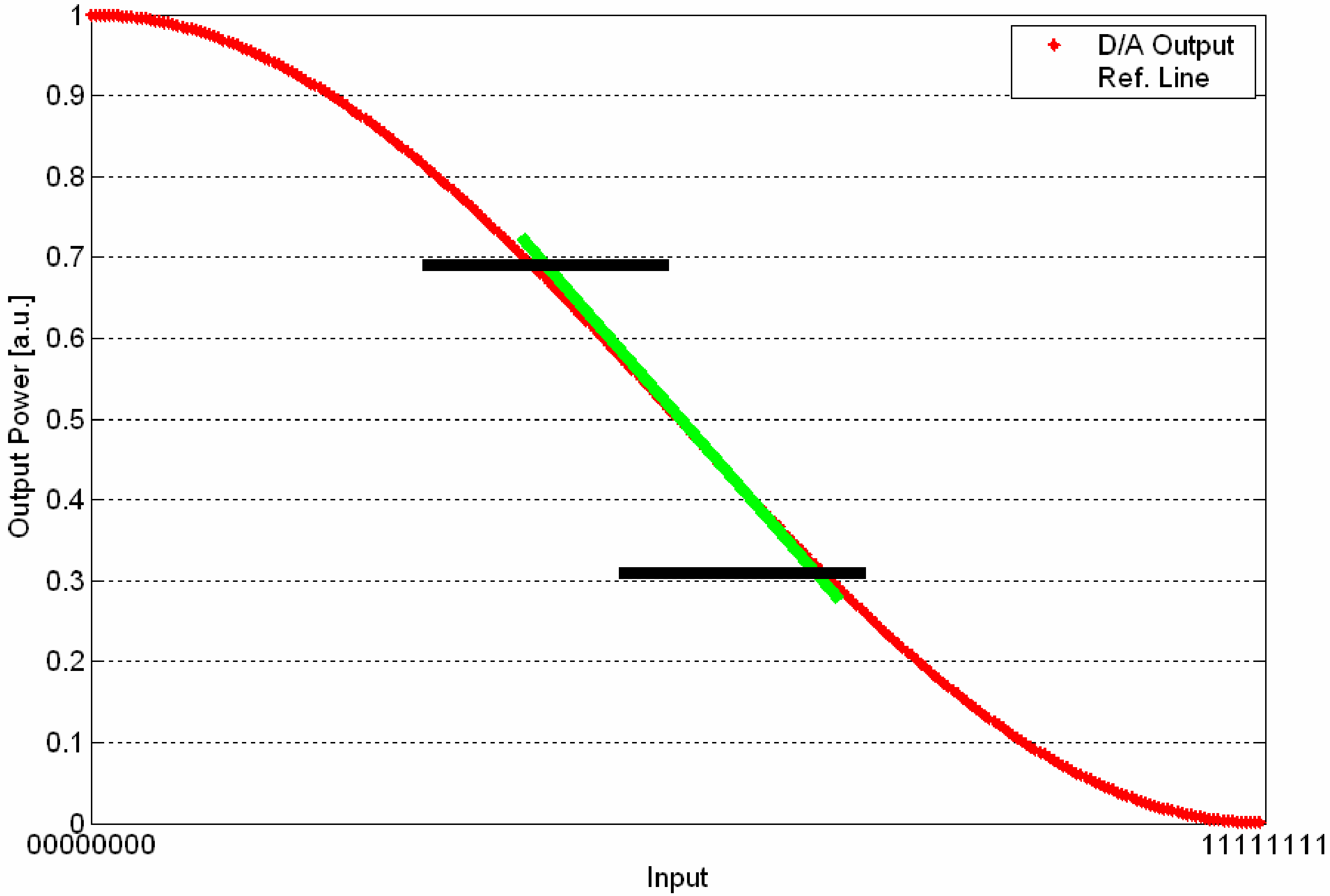




$$T(\mathbf{B_i}) = \cos^2\left(\frac{\pi}{2}\sum_{j=1}^{M} B_{ij}2^{-j} + \phi_{bias}\right) \approx \sum_{j=1}^{M} B_{ij}2^{-j}$$

8-bit Digital Optical Modulator

- Wasted dynamic range!



Full-Dynamic Range Digital Optical Modulator

Digital-To-Digital Conversion

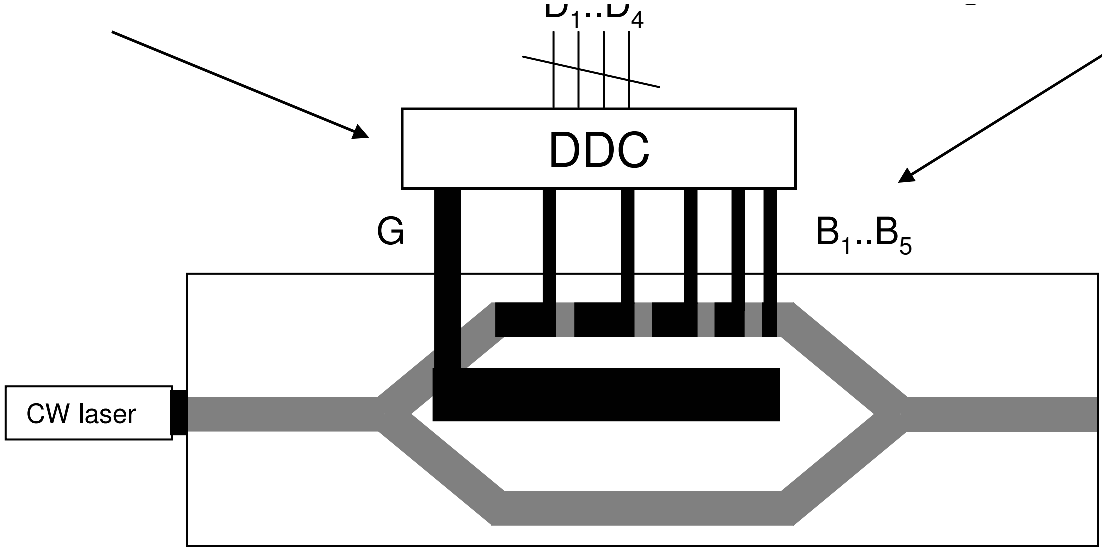
(digital pre-dist

Direct Digital Driving

rode lengths not binary

nted

Number of electrodes M>N



$$T\left(\hat{\mathbf{B}}_{\mathbf{i}},\mathbf{L}\right)=\cos^2\left(\frac{\pi}{2}\sum_{j=1}^{M}\hat{B}_{ij}L_j\right)$$

How to design a good Digital Optical Modulator?

- Convert a digital value into its corresponding analog representation.
- For *N*-bit digital input: $b = (b_1, b_2, ..., b_N)$
- The output of the modulator is an analog value: $I_{out} = f(D)$
- where *f(.)* is (preferably) a linear function of *D* : $D = \frac{b_1}{2} + \frac{b_2}{2^2} + ... + \frac{b_N}{2^N}$
- Integral Non-Linearity (INL) - Measures deviation, in units of LSB, or how close is the output to being a straight line.

How do we find the DDC and the electrode lengths?

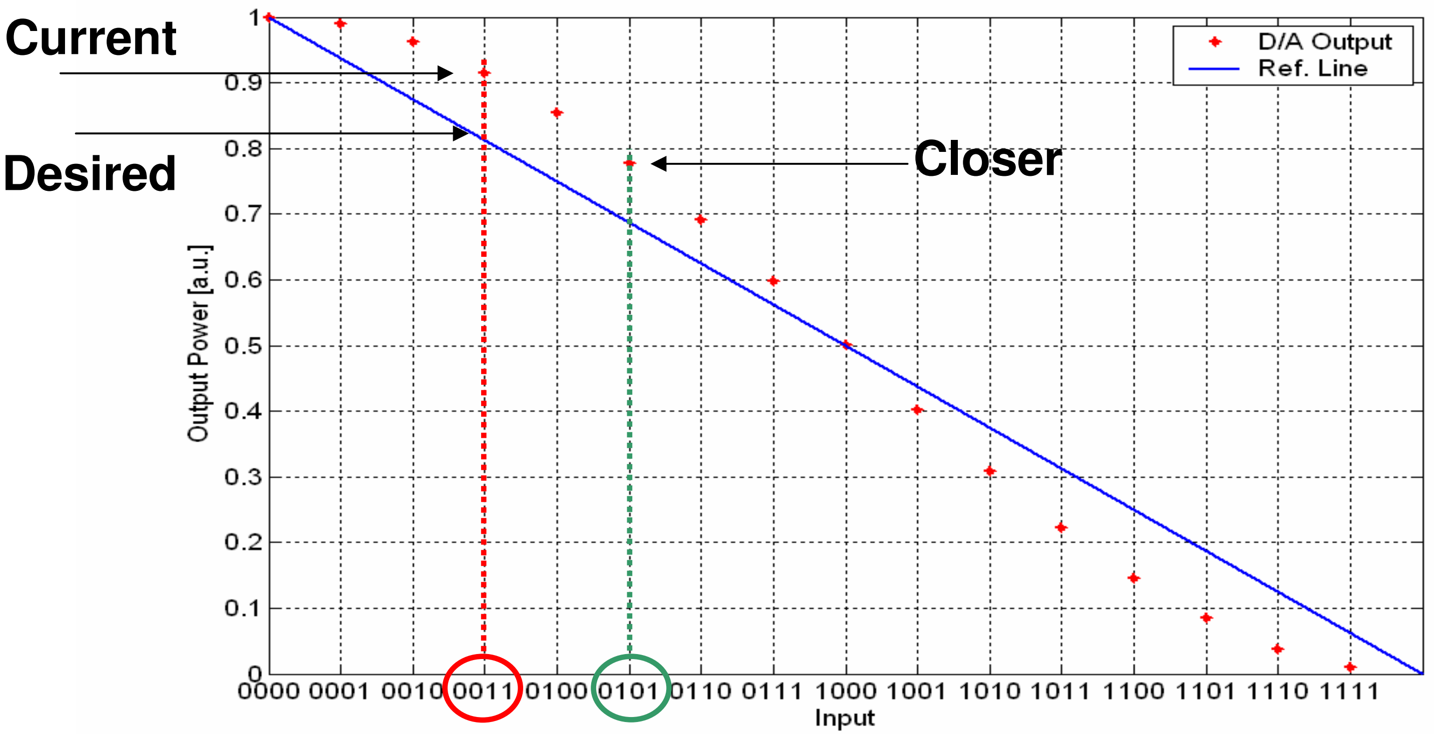
- Minimize goal function:

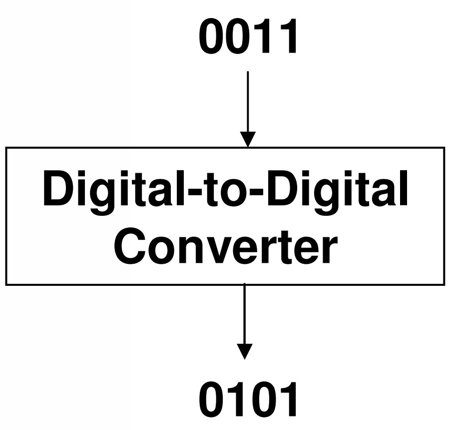
$$\min g(\mathbf{B},\mathbf{L}) = \sqrt{\frac{1}{2^N}\sum_{i=1}^{2^N}\left[U_i - \cos^2\left(\frac{\pi}{2}\sum_{j=1}^{M} B_{ij} L_j\right)\right]},\ U_i = \frac{i}{2^N}$$

- RMSE (Root Mean Square Error) Criterion.
- Optimization Variables:
  - B : Binary (0,1) Matrix.
  - L : Real Vector.

Optimization of B

- Optimization of **B**:
  - Start with $L = 2^{-j}$
  - $\hat{\mathbf{B}}_{\mathbf{i}} = Dec2Bin_M\left(\frac{2}{\pi}\arccos\left(\sqrt{U_i}\right)\right)$





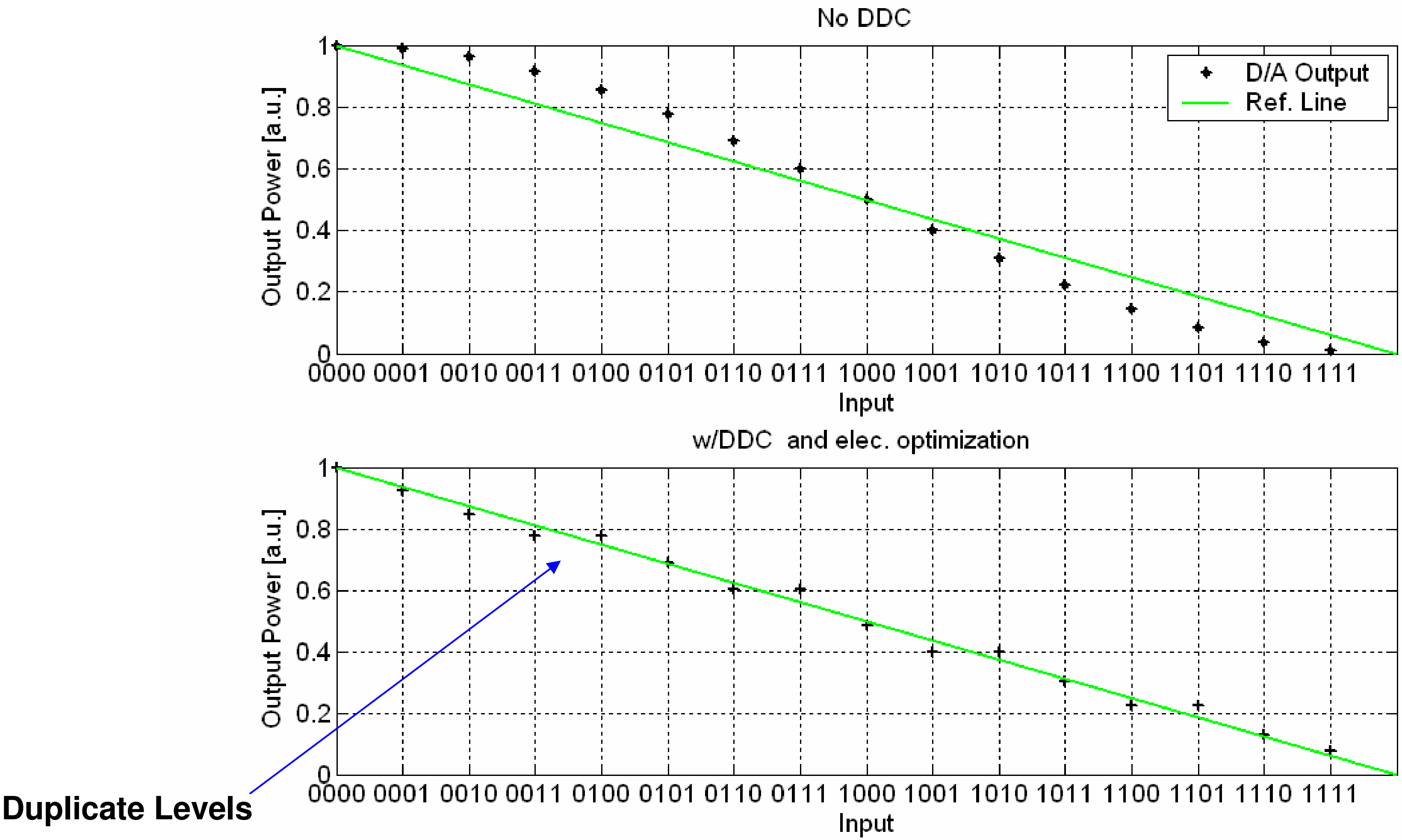
Optimization of L

- Optimization of **L**:
  - Assuming: $$\cos^2\left(\frac{\pi}{2}\sum_{j=1}^{M} B_{ij} L_j\right) \approx U_i ; \forall i$$
  - Equivalent cost function:
$$h(\mathbf{L}) = \left\{\sum_{i=1}^{2^N}\left[\frac{2}{\pi}\arccos\left(\sqrt{U_i}\right) - \sum_{j=1}^{M}\hat{B}_{ij} L_j\right]\right\}$$
  - Differentiate *h(L)* with respect to **L** and get:

$$\mathbf{L} = \left(\hat{\mathbf{B}}^T\hat{\mathbf{B}}\right)^{-1}\frac{2}{\pi}\left[\arccos\left(\sqrt{U_i}\right)\hat{\mathbf{B}}\right]^T$$

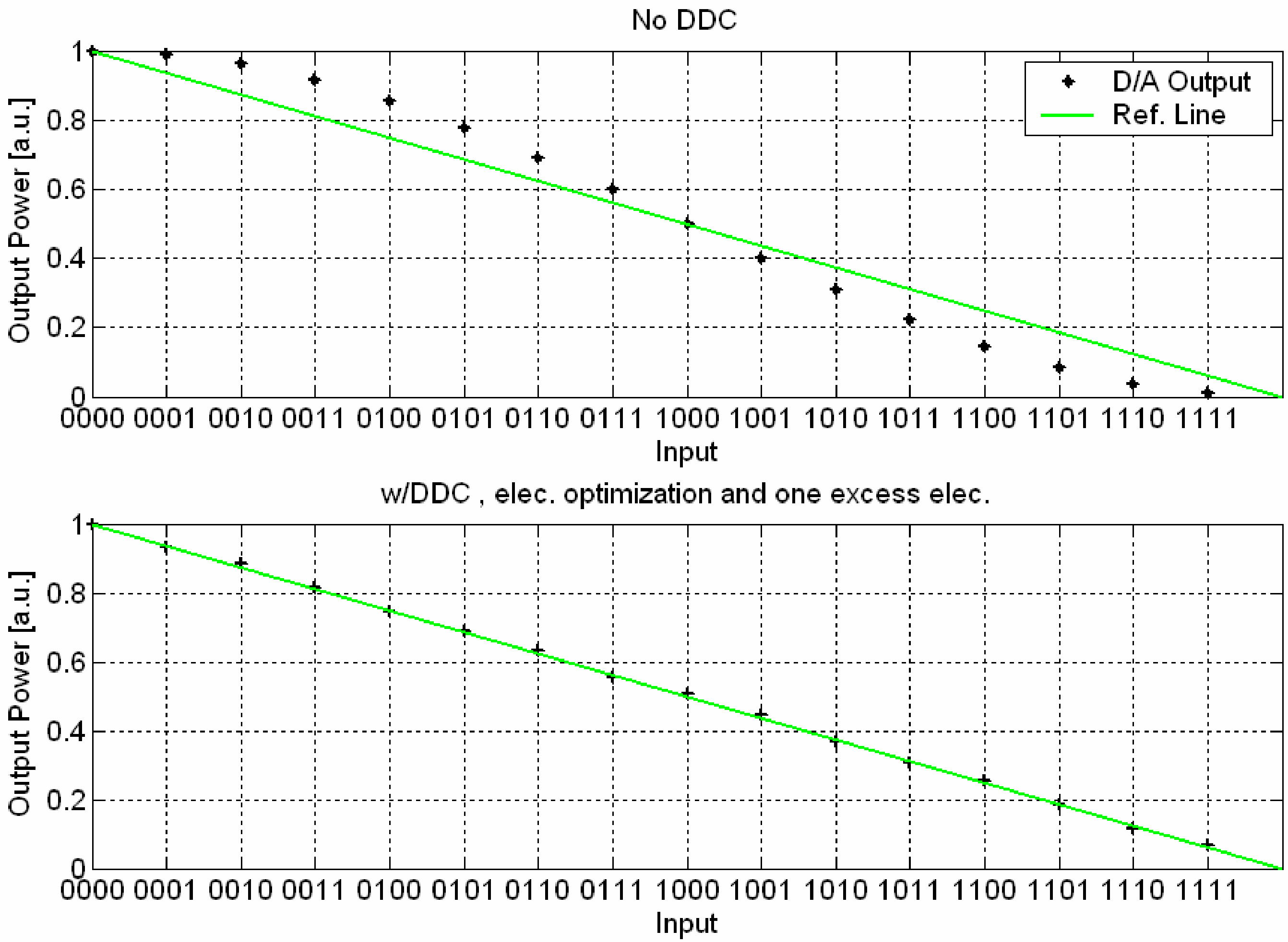
Theoretical Performance 4 bit Digital Optical Modulator

- N=4, M=**4** Number of electrodes equals number of input bits



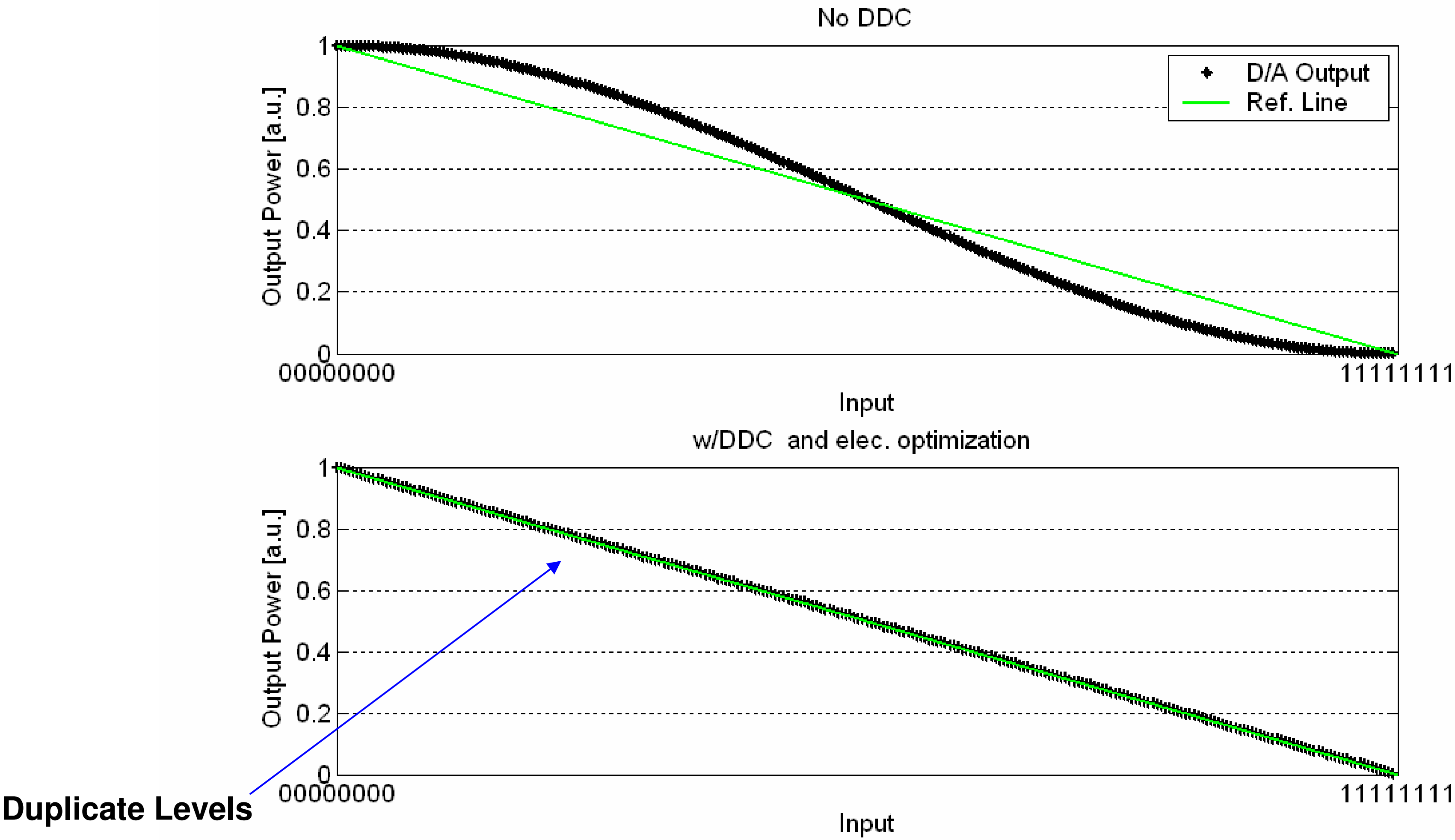
Theoretical Performance 4 bit Digital Optical Modulator

■N=4, M=**5** One excess electrode



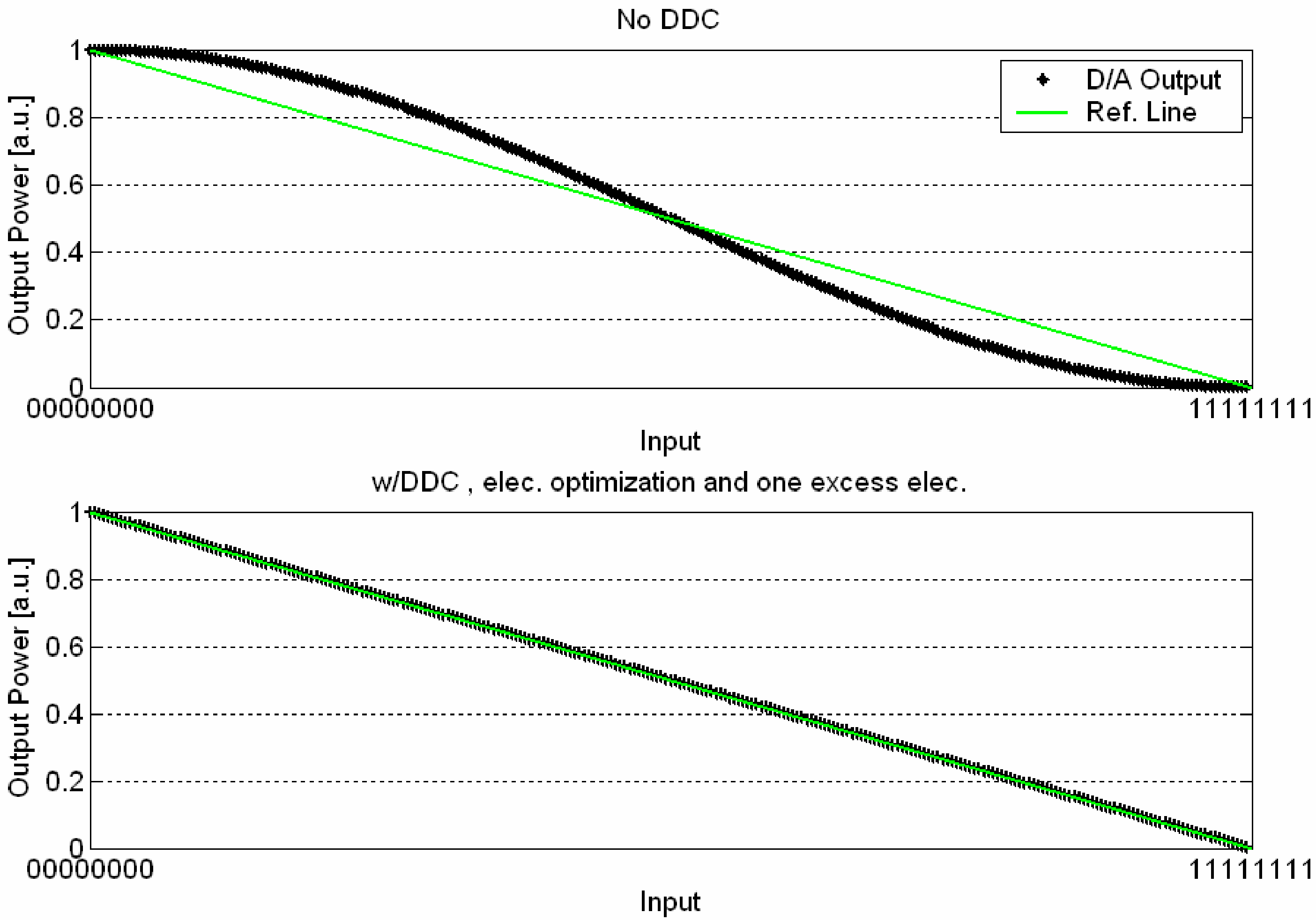
Theoretical Performance 8 bit Digital Optical Modulator

■N=8, M=**8** Number of electrodes equals number of input bits



Theoretical Performance 8 bit Digital Optical Modulator

- N=8, M=**9** One excess electrode



Results

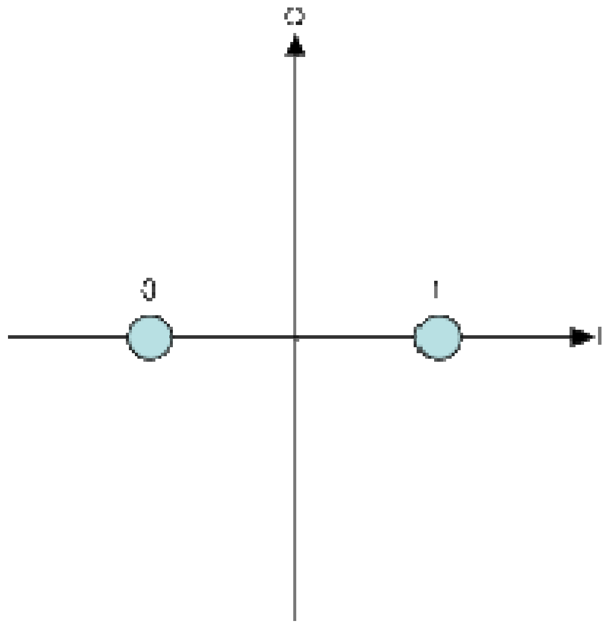
N	M		INL(LSB)	RMSE	aggregate electrodes length
4	4	U	1.6	12.06	0.937
4	4	O	0.72	0.39	0.942
4	5	O	0.16	0.10	0.961
8	8	U	27.52	19.31	0.996
8	8	O	0.77	0.35	0.996
8	9	O	0.41	0.18	0.998

INL is a measure for the output's linearity

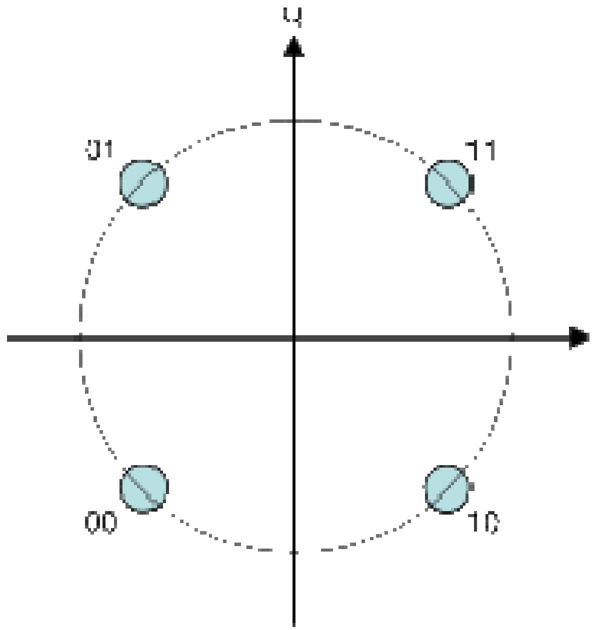
IQ Representation of Signals

- Digital Communication
- Amplitude and\or phase can be used to represent a binary symbol $s_i = r_i e^{j\theta_i}$

PSK

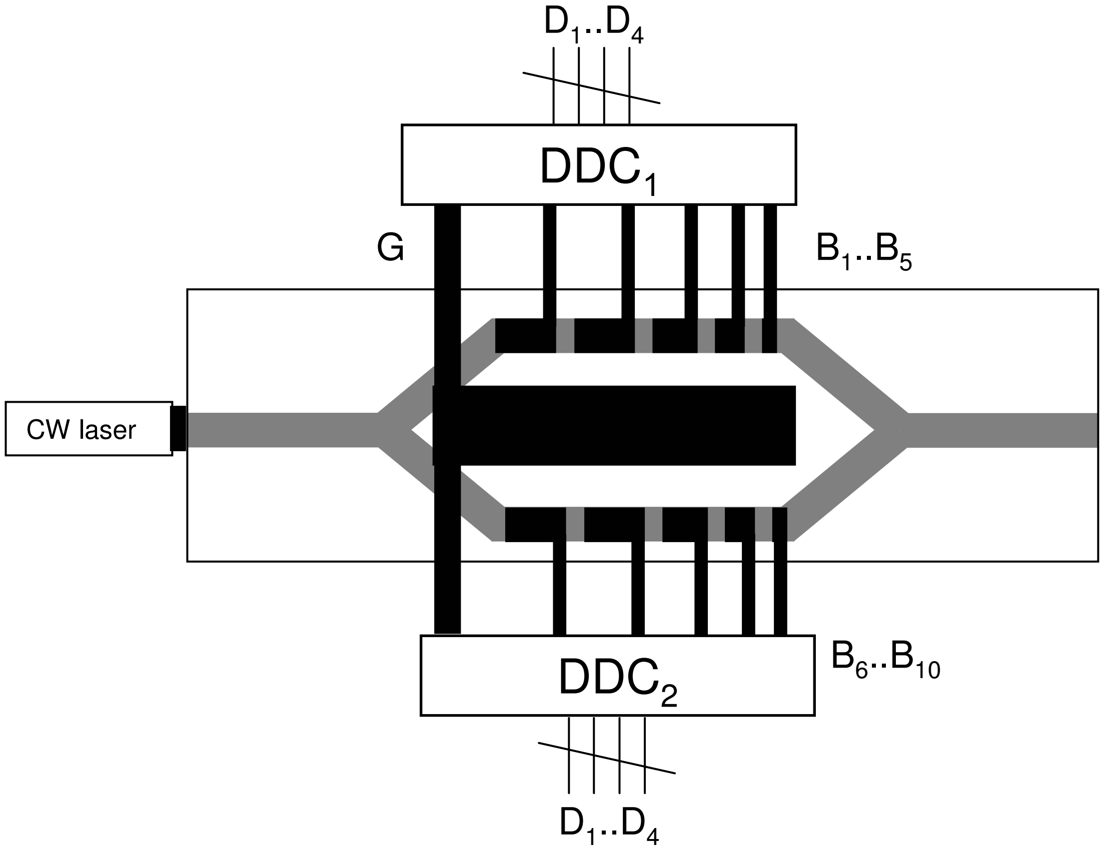


QPSK



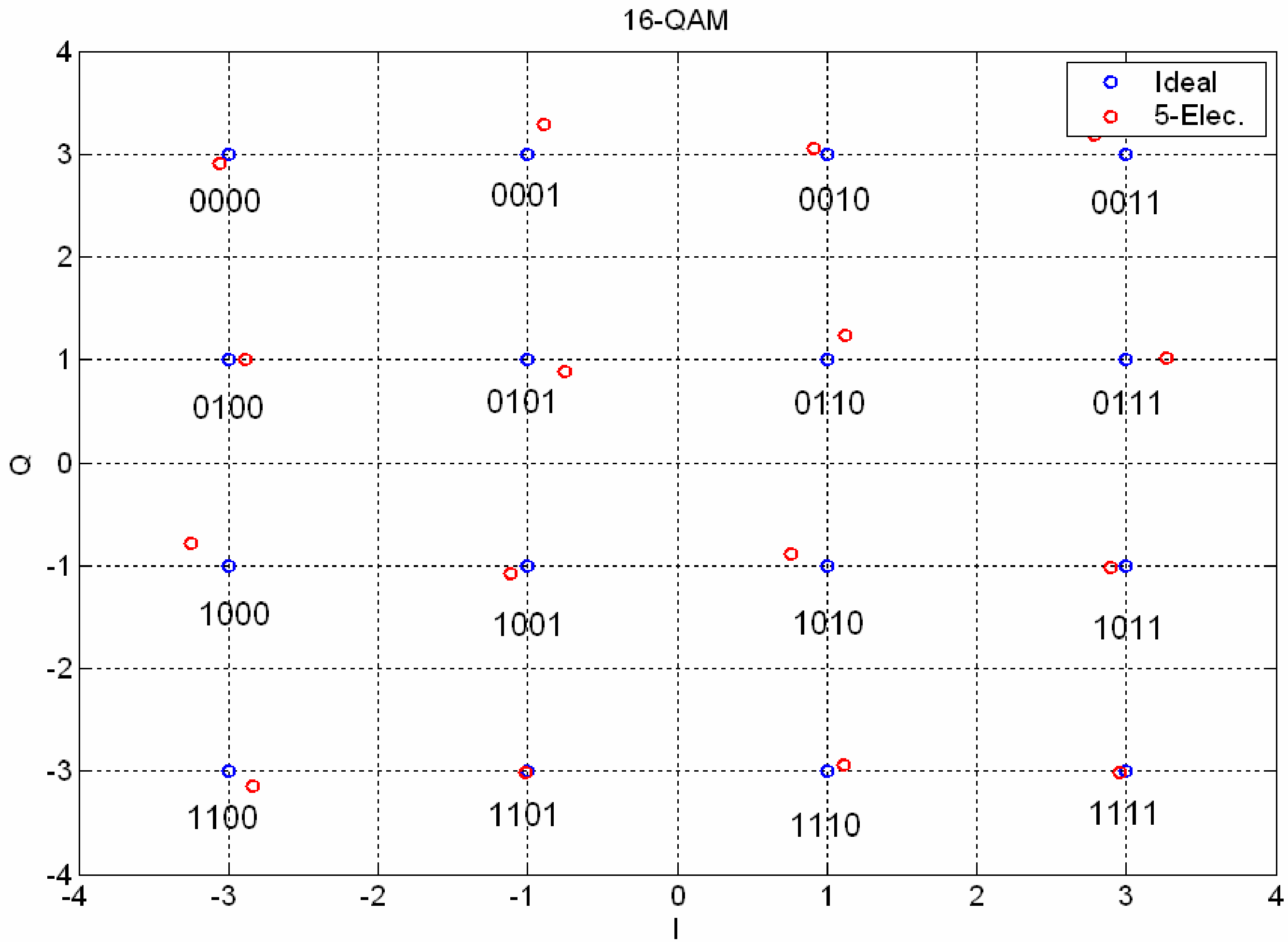
Digital 16-QAM Optical Modulator

- Amplitude and phase are used to represent a binary symbol



IQ Map

■N=4, M=5 One excess electrode



Conclusions

- Multi-Electrode approach for optical computing allows
  - the recruitment of physical light-related quantities, such as intensity, phase.
  - Multi-Level Logic.
- Multi-Electrode approach for interfacing with optical computing device shall consist of
  - Digital pre-distortion (Digital-to-Digital converter).
  - Non-conventional follow-by-2 electrode sectioning.
  - Number of electrodes may be higher than the number of bits.

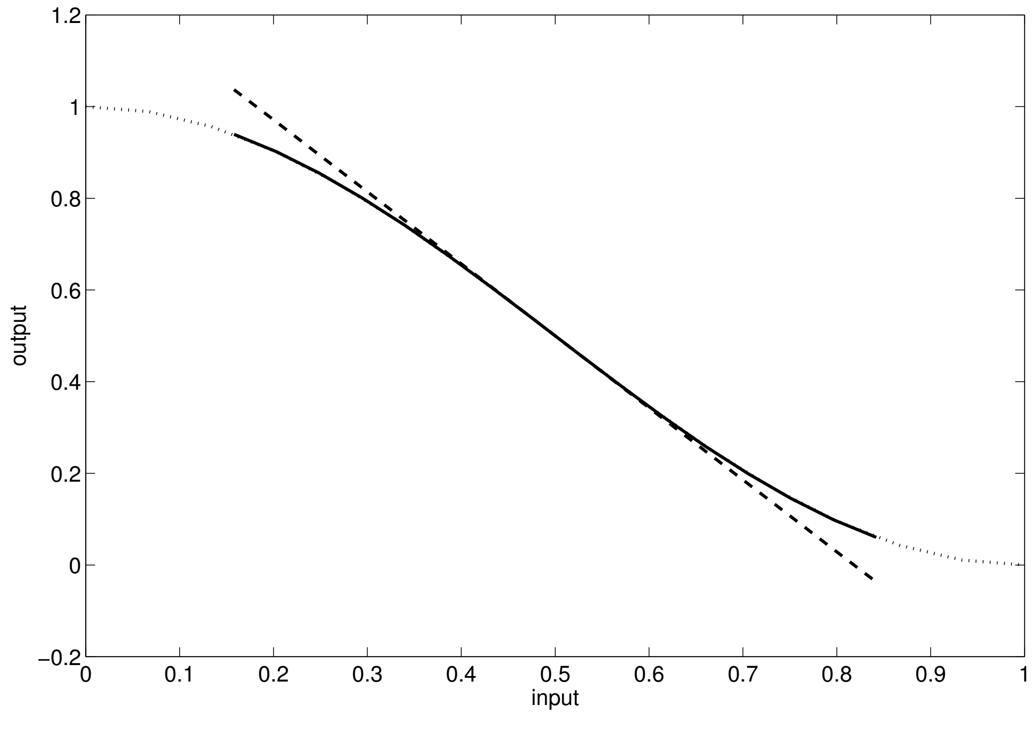
Conclusions

- Modulate other physical quantities such as polarization and wavelength
- Different goal functions and logic schemes.
- Application to other types of optical modulators: EAM, DCM, Direct Modulation.

The END

Linearity and Dynamic Range

- When trying to increase the dynamic-range, linearity quickly deteriorates.



FDR vs. Biased