Large Dynamic Range Electromagnetic Field Sensor based on Domain Inverted Electro-Optic Polymer Directional Coupler

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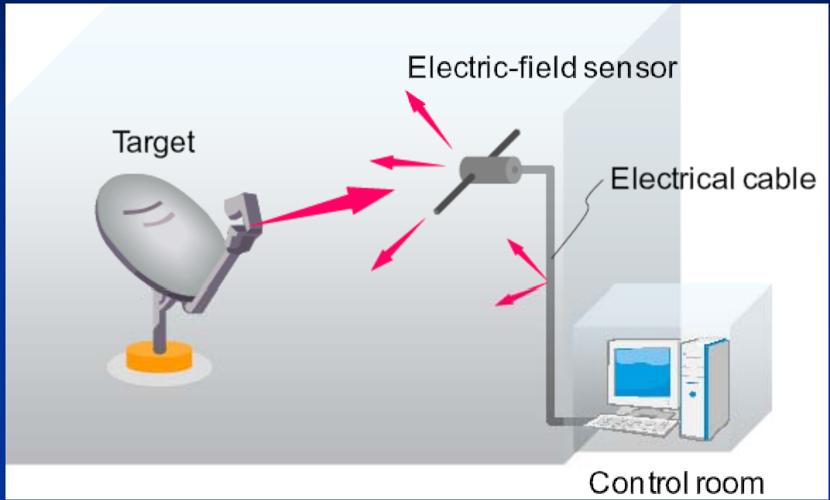
Application of Electric Field Sensors:

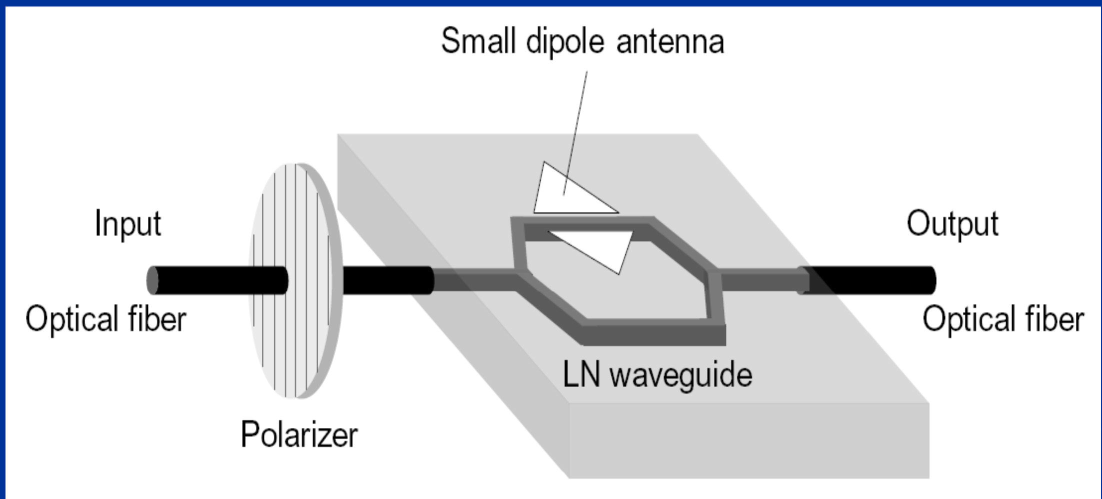
- Electromagnetic Attack Alarming
- Medical Apparatuses
- Microwave-Integrated Circuit Testing
- Ballistic Control
- Health Protection (<100KHz)

Electronic Sensor v.s. Photonic Sensor



Drawbacks of Conventional Electronic Sensor:

- **Disturbance from electrical cables**
- **Narrow bandwidth**
- **Bulky size**

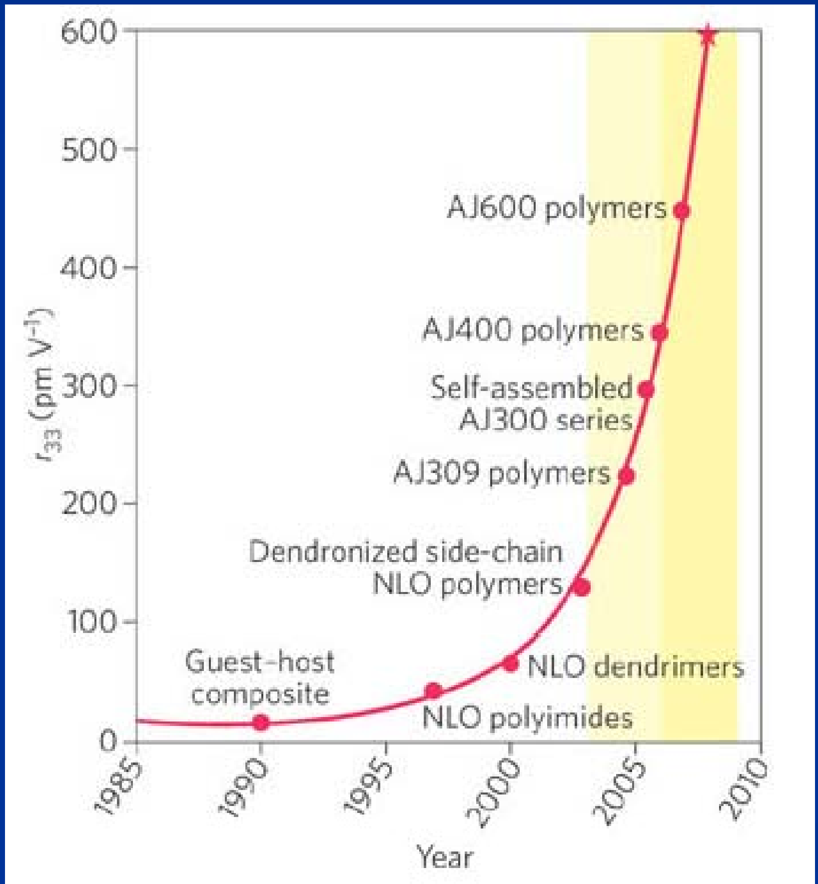


Advantages of Photonic EM Sensor:

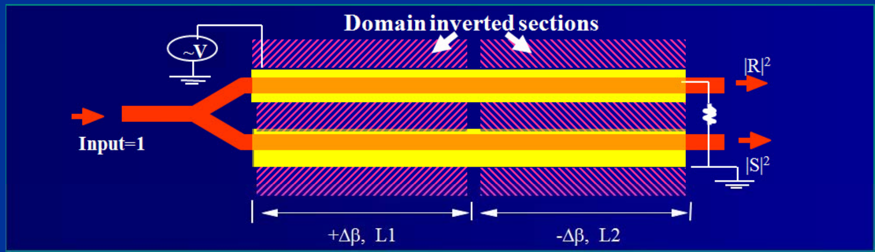
- **Free of disturbance to EM waves**
- **Broad bandwidth**
- **Compact size**
- **Precise measurement**

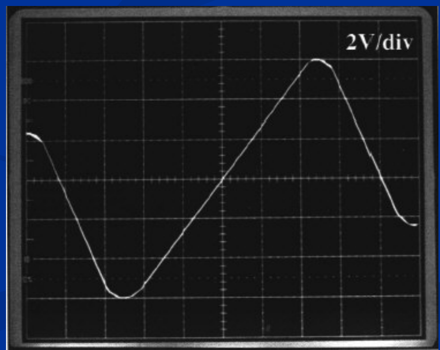
Domain Inverted E-O Polymer Directional Coupler with Super High Dynamic Range

DARPA MORPH E-O Polymer

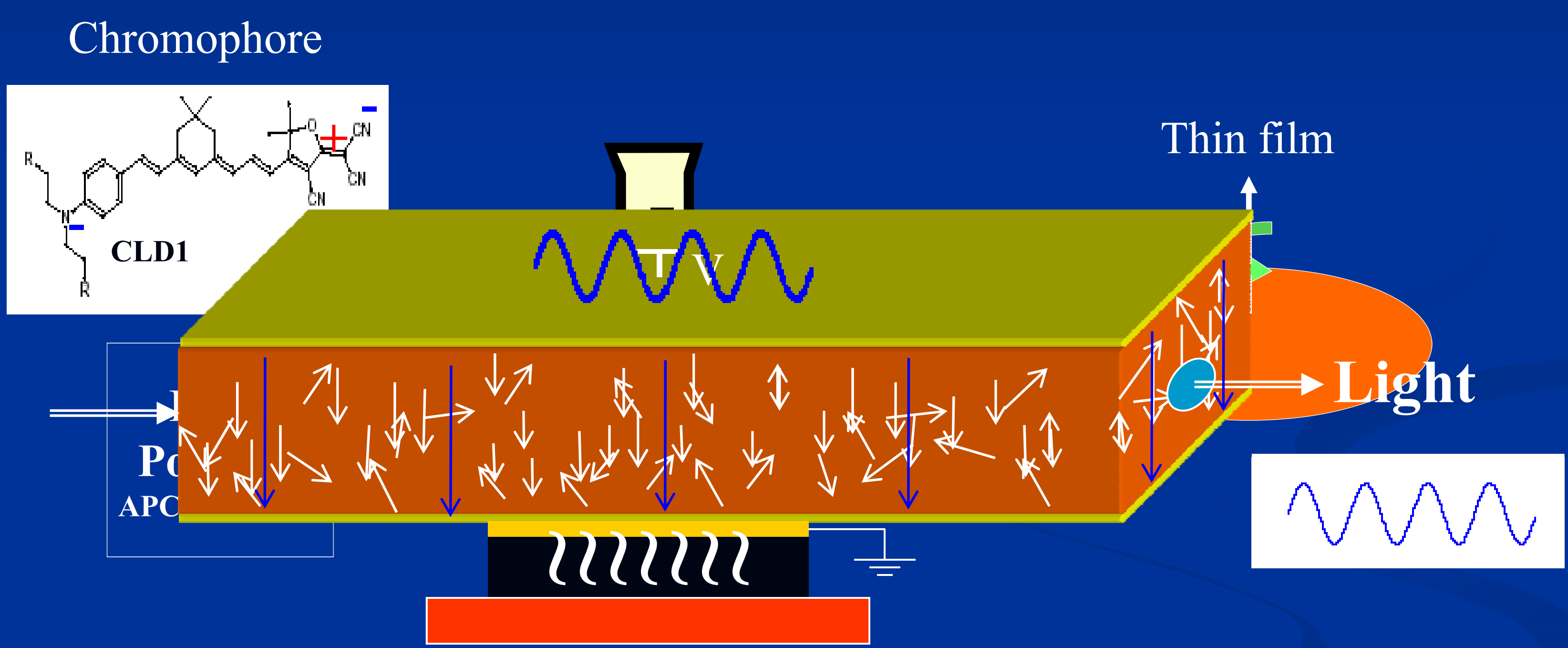


Domain Inverted Y-fed Directional Coupler





What is E-O Polymer Materials?



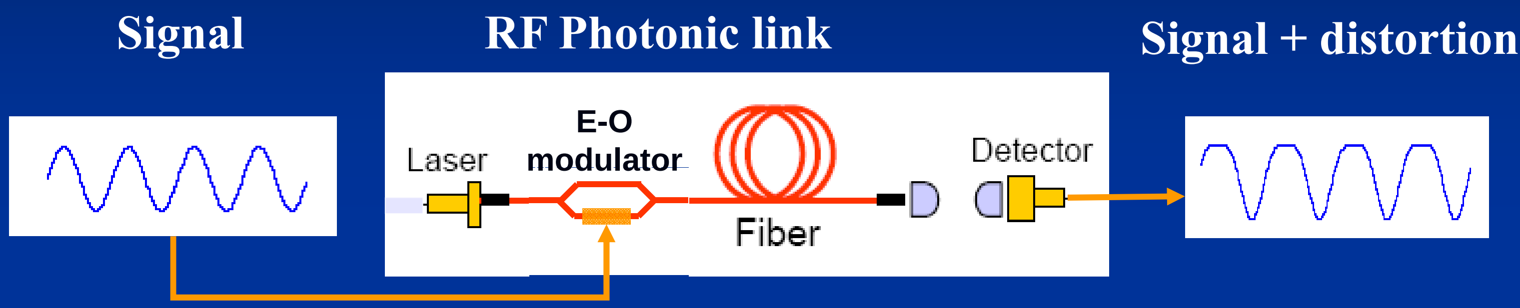
Pockels effect: $\Delta n = -\frac{1}{2} n^3 \gamma E$

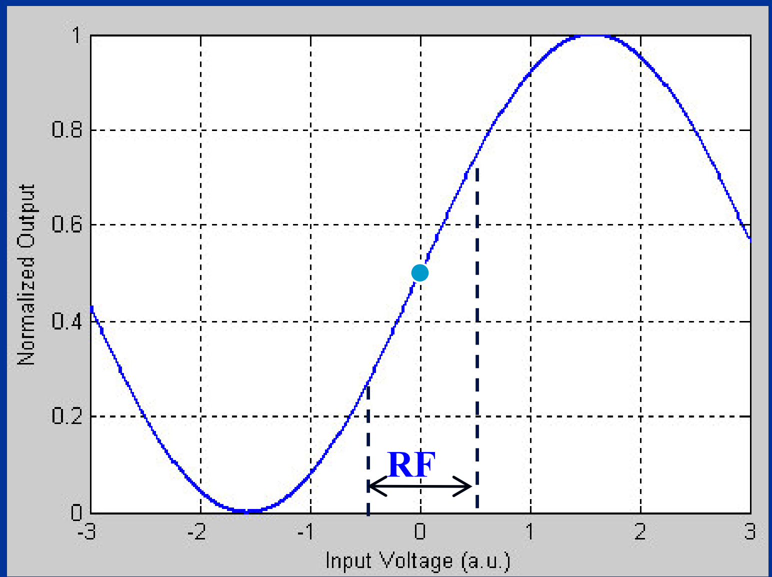
Materials Comparison

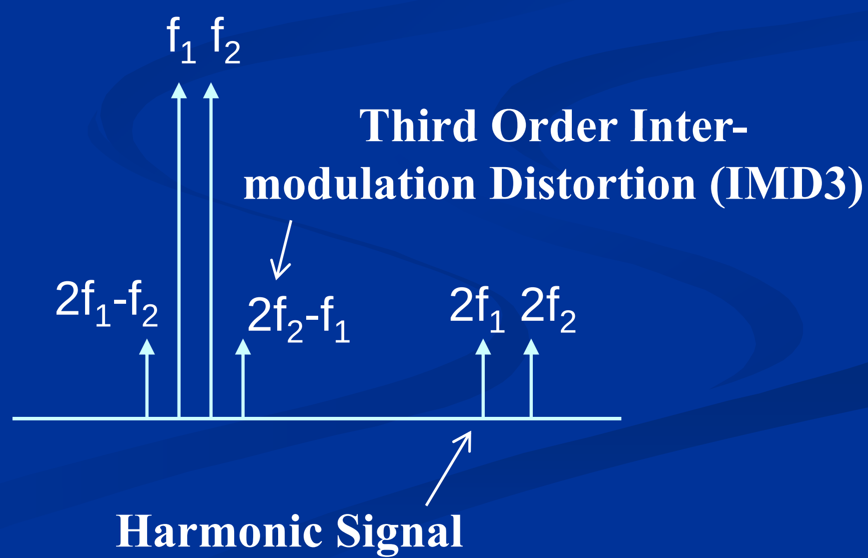
Materials	Polymers	Si/SOI	III-V	$LiNbO_3$
Optical Loss (dB/cm @1550nm)	~1	0.2	~0.5	0.2
E-O efficiency (pm/V)	450	N/A	<5	30
Bandwidth (GHz)	110	40	30	40
Fabrication Process	Various	CMOS	RIE	Ti diff.
Integration	Easy	Standard	Difficult	No
Cost	Low	Low	Highest	High
Reliability	Moderate	High	High	High
Improvement Potential	Yes	No	No	No

➢Design of Domain Inverted E-O Polymer Directional Coupler

Nonlinear Distortion in RF Photonics

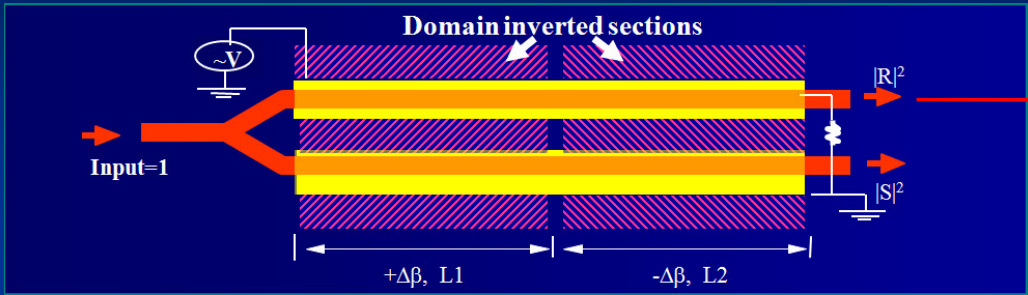


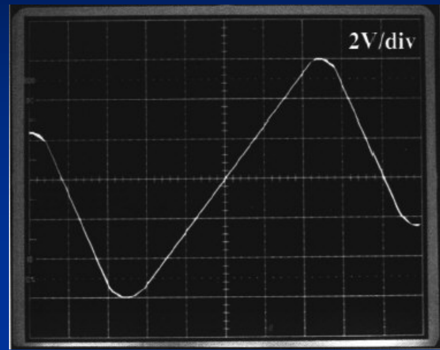




$$I_{out} = \frac{I_0}{2} + \frac{I_0}{2}\cos[\phi_{bias} + \Delta\phi(V)]$$

Y-fed Directional Coupler based on Domain-Inverted Waveguide





$$\begin{bmatrix} R_o \\ S_o \end{bmatrix} = M_2 M_1 \begin{bmatrix} R_i \\ S_i \end{bmatrix} = \begin{bmatrix} A_2 & -jB_2 \\ -jB_2^* & A_2^* \end{bmatrix} \begin{bmatrix} A_1 & -jB_1 \\ -jB_1^* & A_1^* \end{bmatrix} \begin{bmatrix} R_i \\ S_i \end{bmatrix}$$

R, S: Complex amplitude

H. Kogelnik and R. V. Schmidt, "Switches directional couplers with alternating Δß", *IEEE J. of Quantum Electron.*, vol. 12, pp. 396-401, July 1976

$$|R|^2 = f(V) = \frac{1}{2} + \sum_{n=1}^{\infty} h_n V^n$$

$$h_n = \frac{1}{n!} \frac{d^n f(V)}{dV^n}$$ are the Taylor coefficients

Analytical Methods:

- Reduced simulation work
- Full spectrum coverage
- Small errors

Expression and amplitude of the signals from the Y-fed directional coupler

Signal	Frequency	Amplitude (up to the 7th order expansion)
DC	0	1/2
Fundamental	f_1, f_2	$\frac{1225}{64}h_7a^7+\frac{25}{4}h_5a^5+\frac{9}{4}h_3a^3+h_1a$
2nd Harmonic	$2f_1$, $2f_2$	0
IMD2	f_1-f_2, f_1+f_2	0
3rd Harmonic	$3f_1$, $3f_2$	$\frac{441}{64}h_7a^7+\frac{25}{16}h_5a^5+\frac{1}{4}h_3a^3$
IMD3	$2f_1-f_2$, $2f_2-f_1$	$\frac{735}{64}h_7a^7+\frac{25}{8}h_5a^5+\frac{3}{4}h_3a^3$
….		

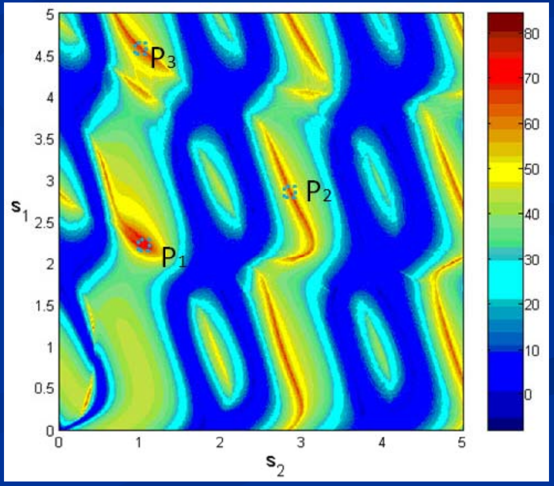
How to characterize the linearity of the optical modulators?

$$V=a[\sin(2\pi f_1t)+\sin(2\pi f_2t)]$$

IMD3 is the most important spurious signal because:

It has the largest magnitude

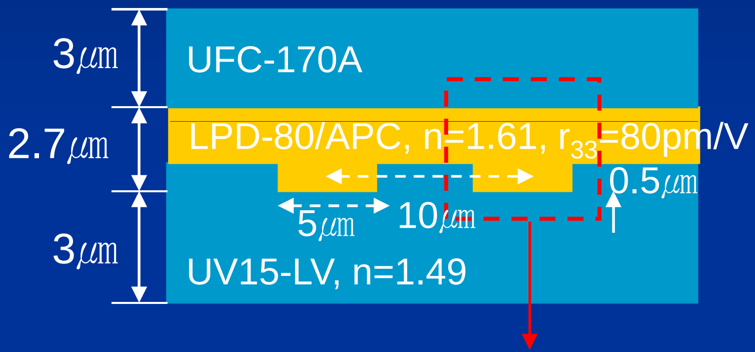
It is very close to the fundamental signals

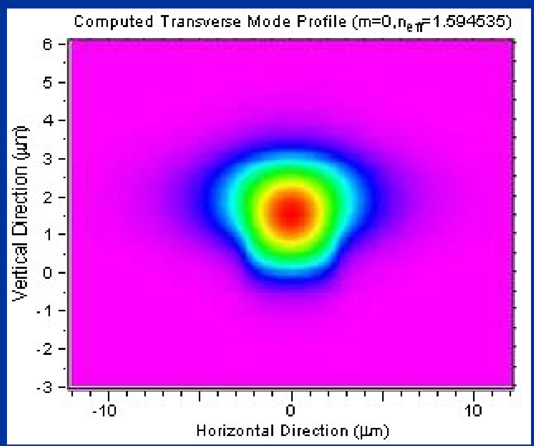


IMD3 suppression at 10% modulation depth

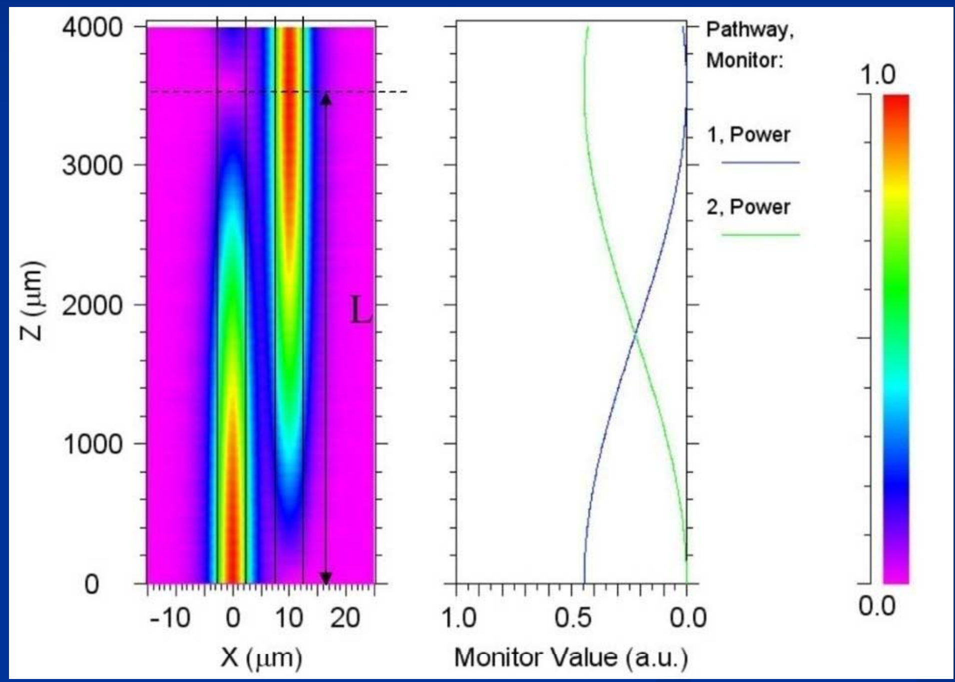
Design of Domain Inverted Modulator

Schematic of the waveguide structure



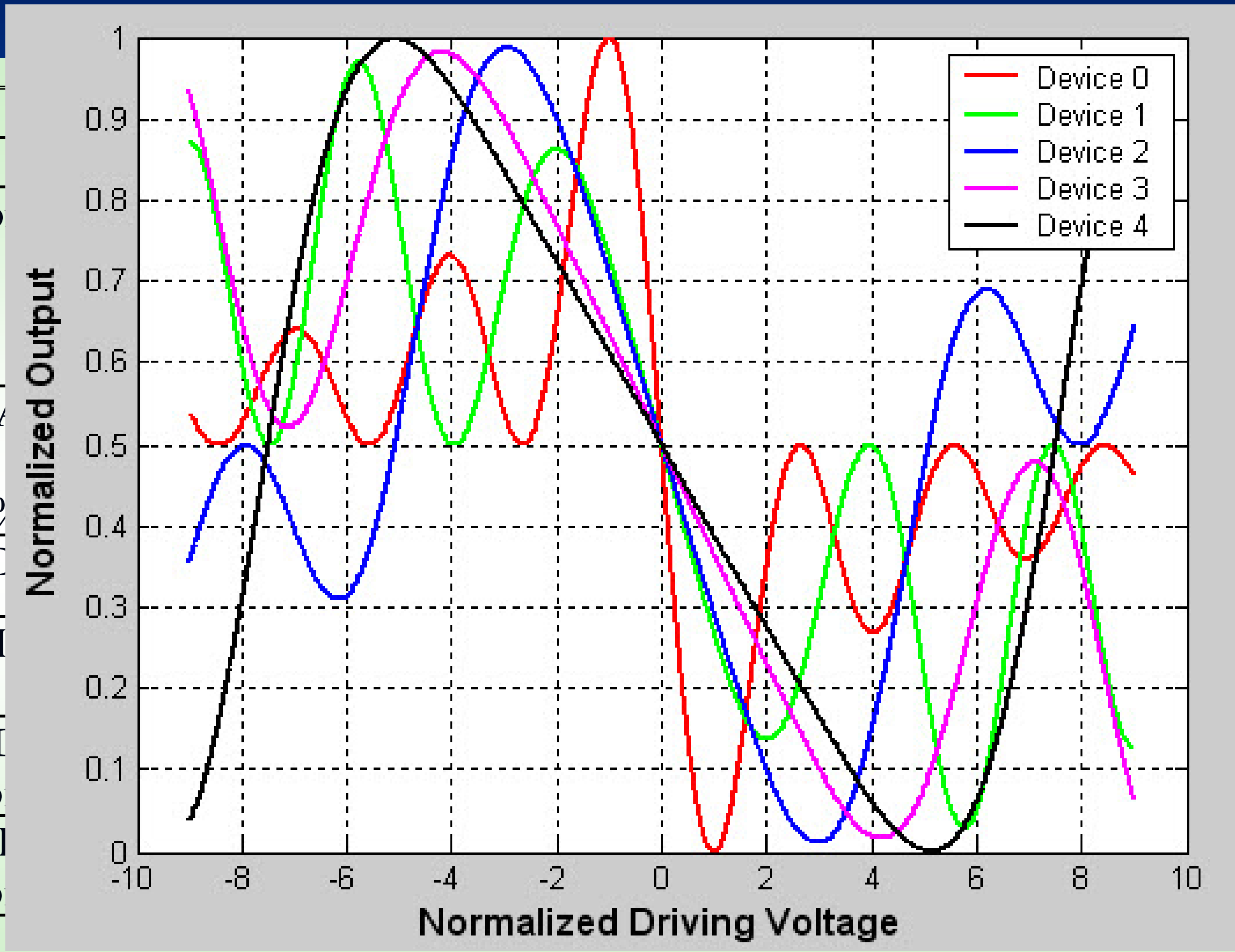


Simulation of the conversion length



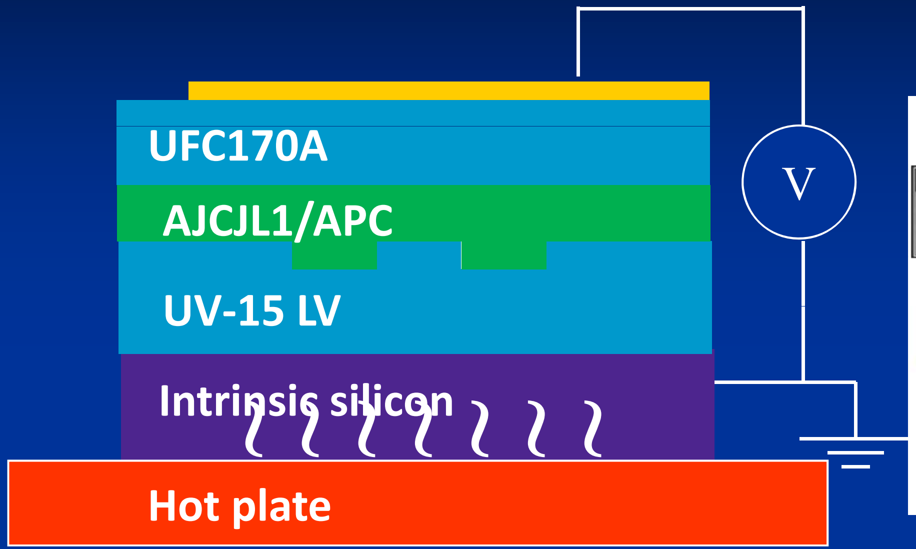
Coupling length :*lc*=3.55mm at λ=1.55㎛

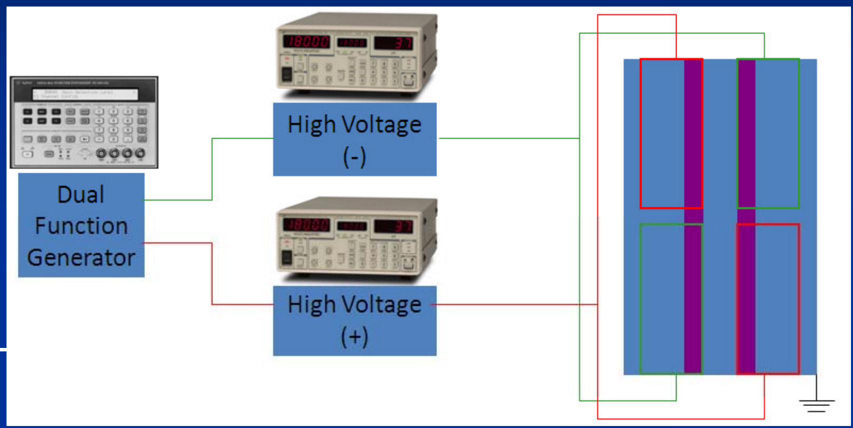
Performances of YFDCs with different number of domains

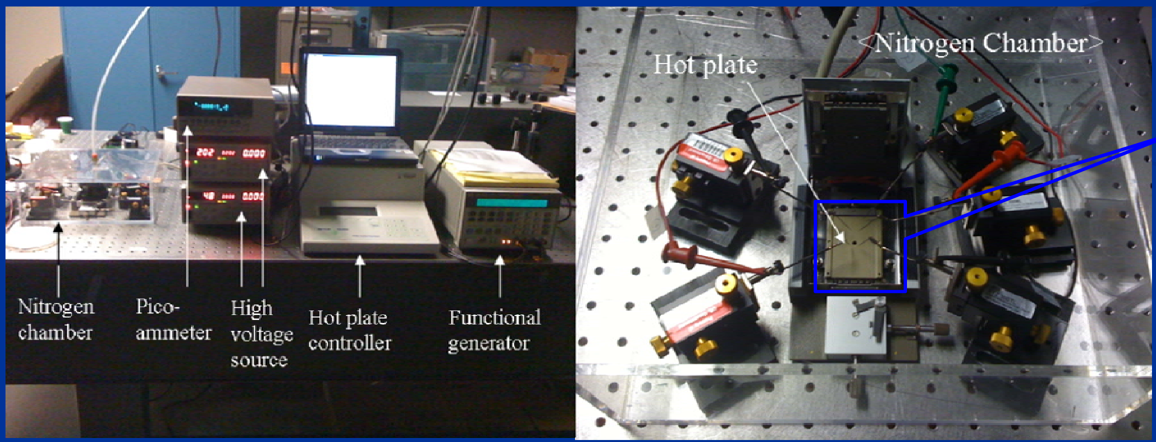


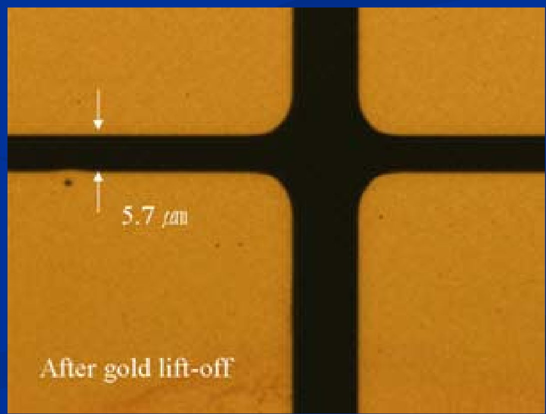
	Device 4
	4-domain
No	s_1=2.1884 s_2=2.2058 s_3=1.5383 s_4=2.6648
A 10%	110.3
D	5.12
M	99.7%
SFI no	120
SFI no	130

➢Device Fabrication

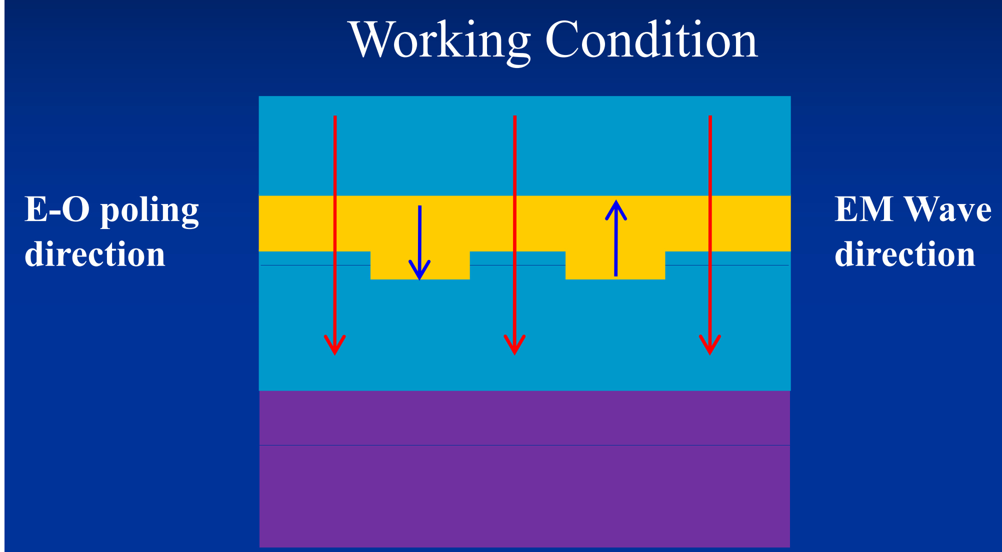


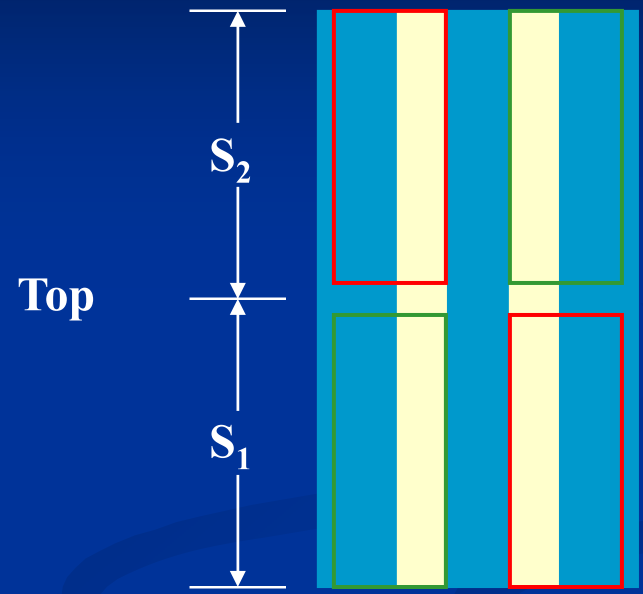


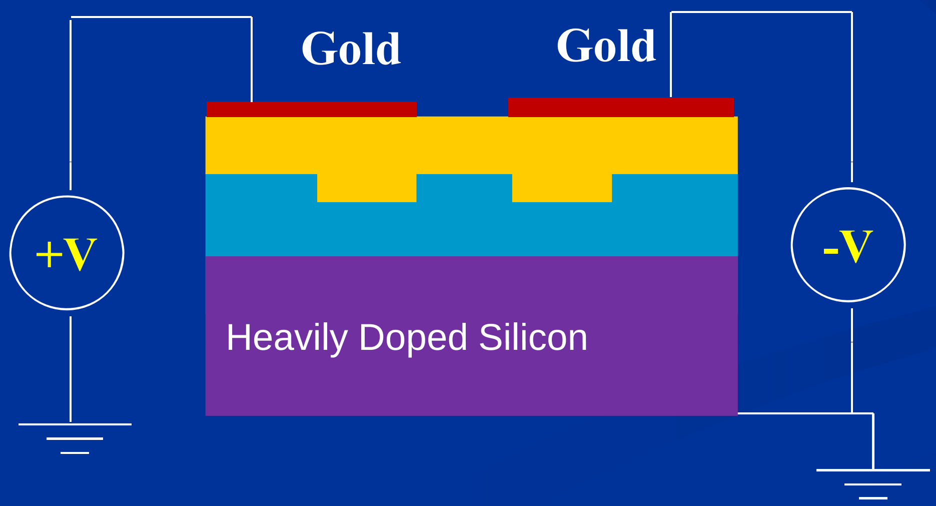




Domain Inverted E-O Poling by Pulse Voltage



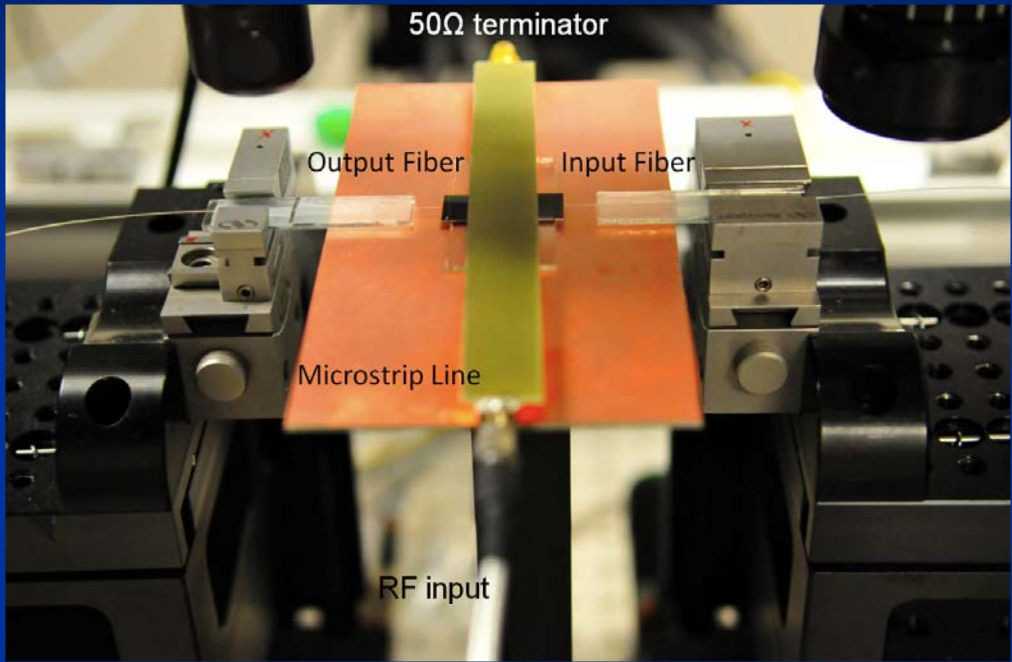


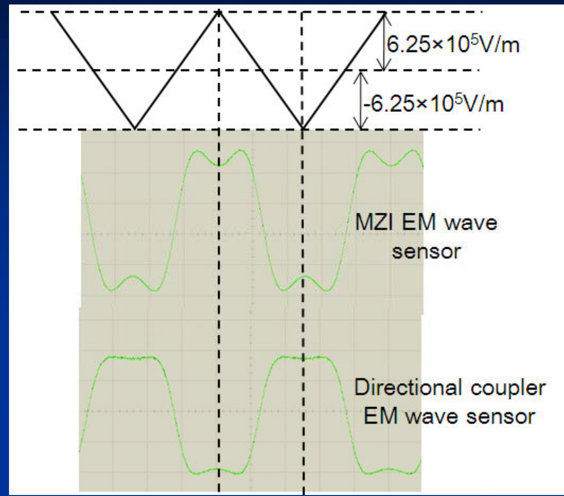


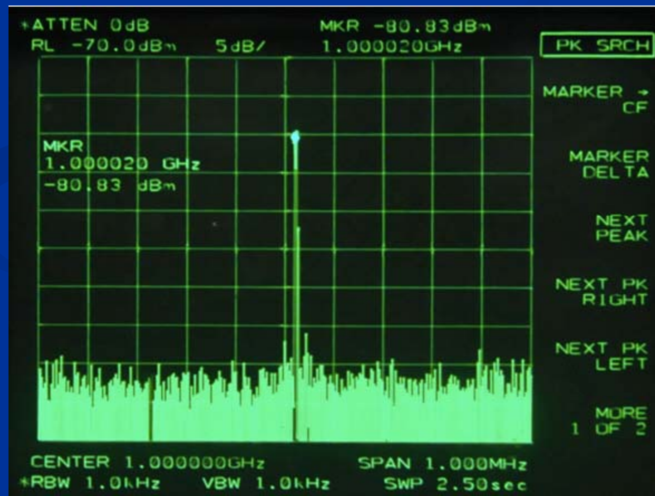
Key Points:

- **E-O poling without top cladding**
- **Domain inverted poling**
- **No bottom electrode**

➢E-O Polymer Photonic EM Wave Sensor Characterization

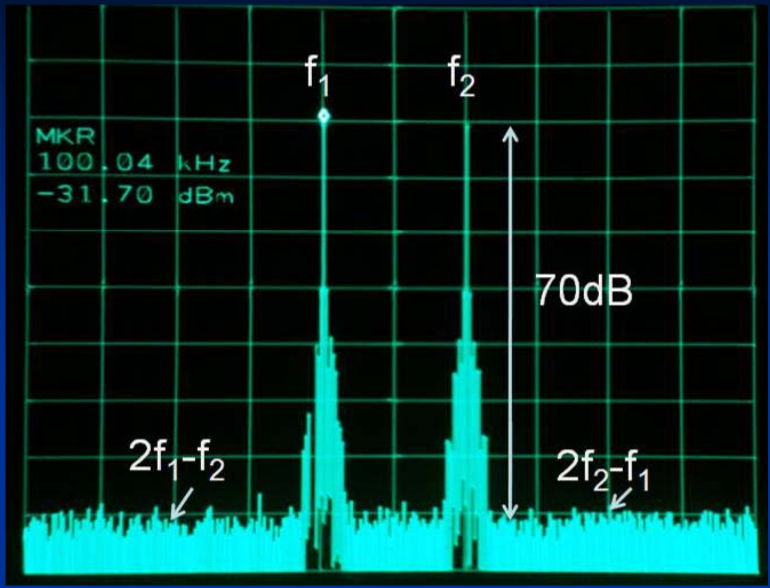






RF response @ 1GHz

- **Xiaolong Wang**, Beom-Suk Lee, Ray T. Chen, "Large Dynamic Range Electromagnetic Field Sensor based on Domain Inverted Electro-Optic Polymer Directional Coupler," Invited Presentation, SPIE Photonics West conference, RF and Millimeter-Wave Photonics (Conference 7936), San Francisco, January 22-27, 2011



$$< S >= \frac{\varepsilon_0 c}{2} E^2$$

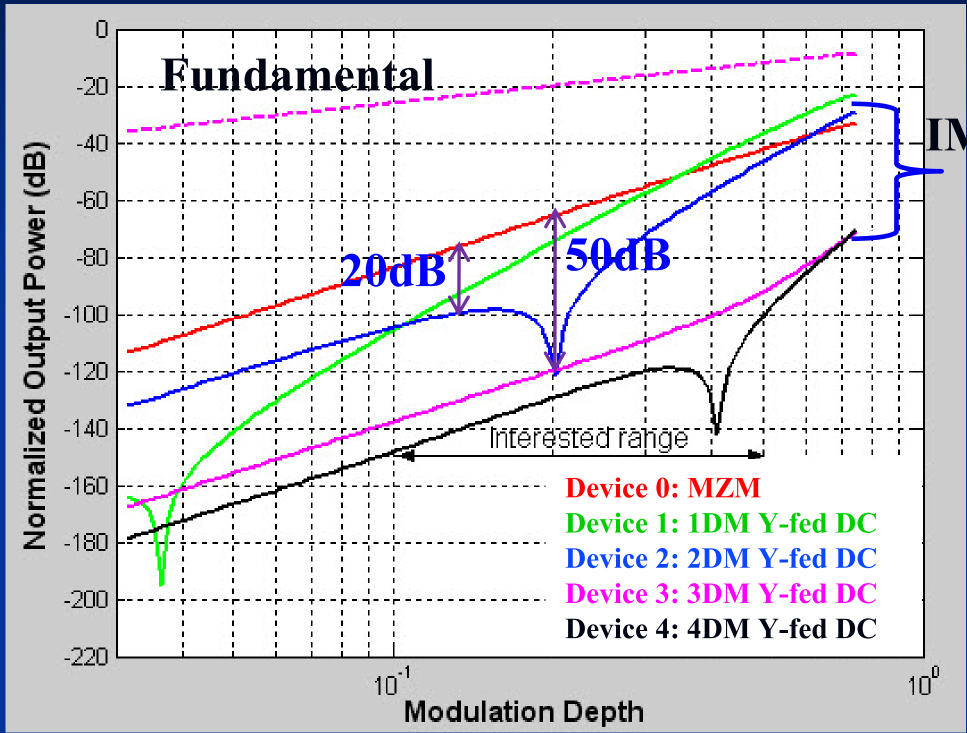
where $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m
$c = 3 \times 10^8$ m/s
E is the maximum amplitude of the electric field

	Electric Field	RF Power Density
Minimum	30V/m	$0.32 mW/cm^2$
Maximum	4×10^5 V/m	$59 KW/cm^2$

Solicitation Requirement: milliwatts per square centimeter to kilowatts per square centimeter

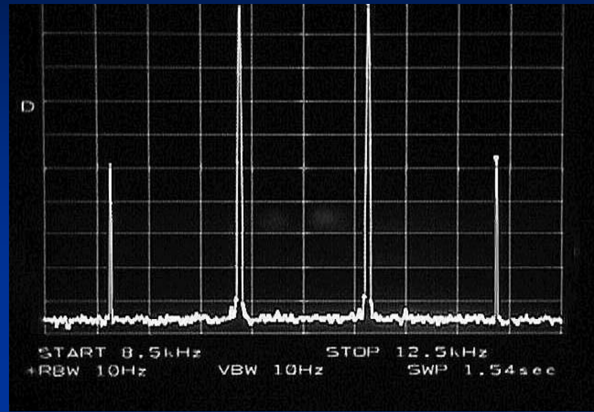
Exactly Matched!

IMD3 Suppression

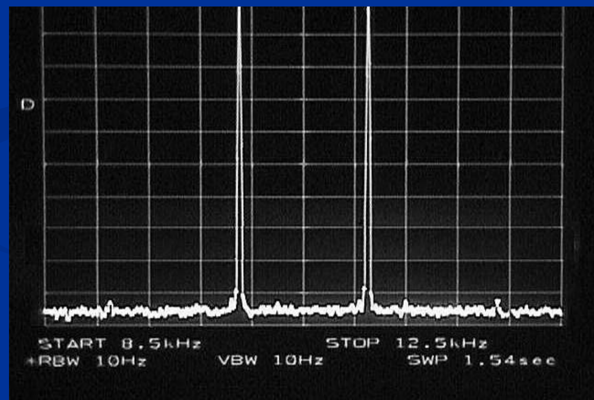


22dB higher average IMD3 suppression from 10%~50% modulation depth

MZ Modulator



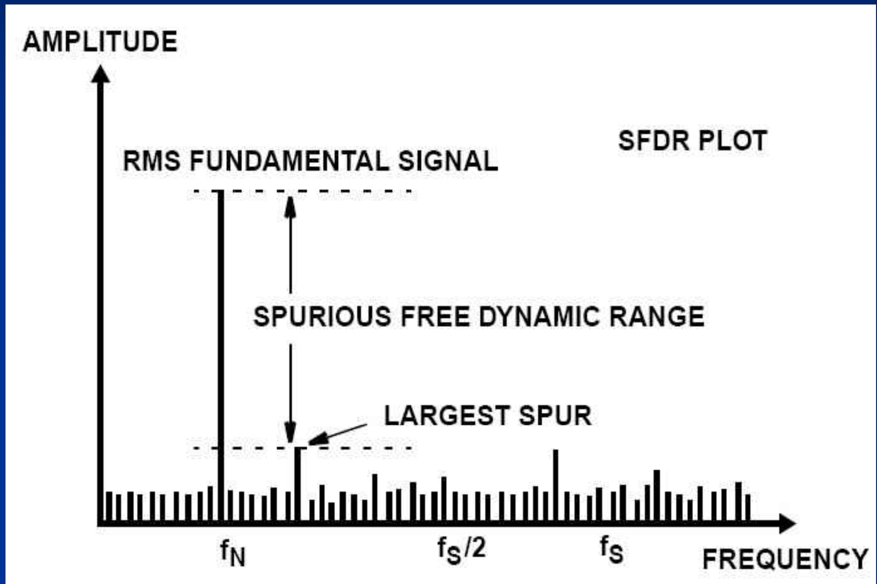
Linear Modulator



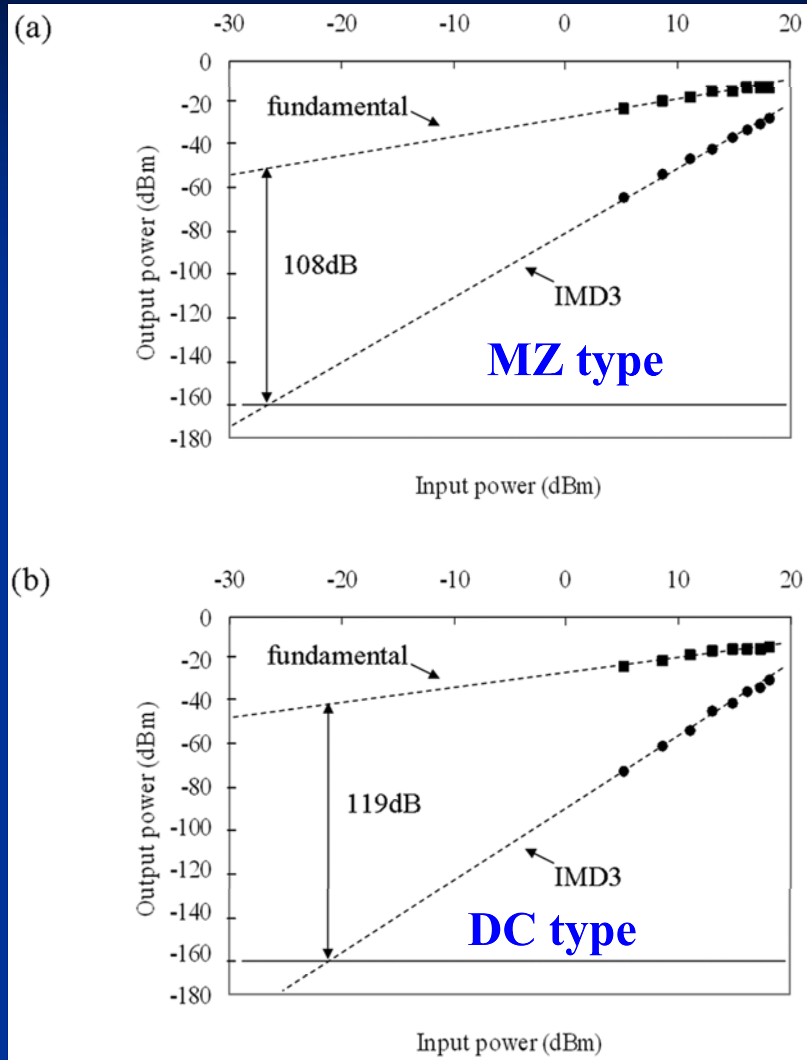
47dB higher IMD3 suppression @ 20% modulation depth

- Boem-Suk Lee, Che-Yun Lin, **Xiaolong Wang**, Jingdong Luo, Alex K.Y. Jen, and Ray T. Chen, "Bias-free electro-optic polymer based two-section Y-branch waveguide modulator with 22-dB linearity enhancement," *Optics Letters*, Vol.34, No.21, pp.3277-3279 (2009)

Spurious Free Dynamic Range



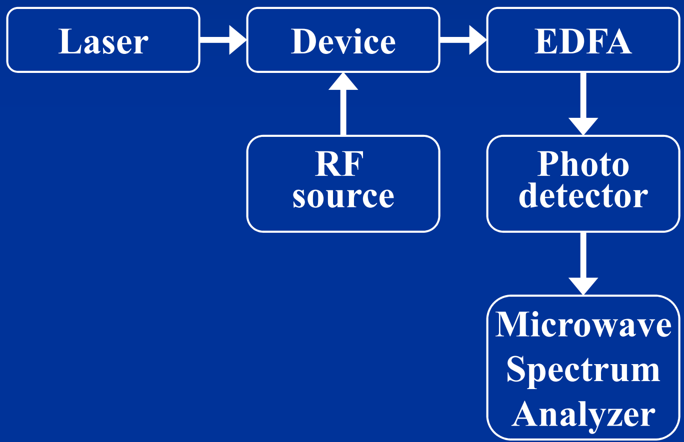
Definition of Spurious Free Dynamic Range (SFDR)

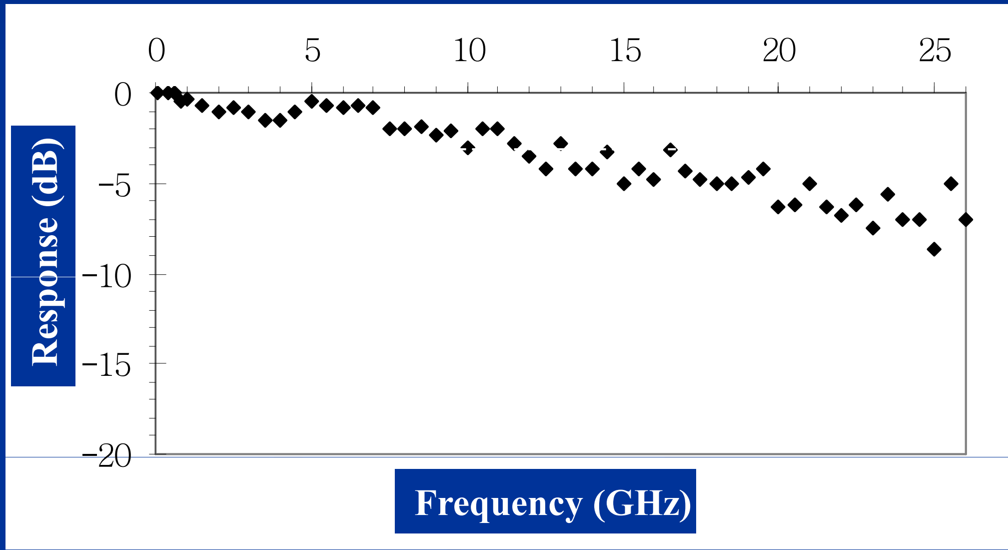


- Beomsuk Lee, **Xiaolong Wang**, Ray T. Chen, and Raluca Dinu, "Electro-Optic Polymer Y-Brunch Directional Coupler Modulator with High Linearity," submitted to *IEEE Photonic Technology Letters*

11dB higher SFDR!

Small Signal Modulation Measurement





λ=1.55㎛

Modulation depth = 4%

Frequency range ~26.5GHz

3-dB electrical bandwidth ~ 10GHz