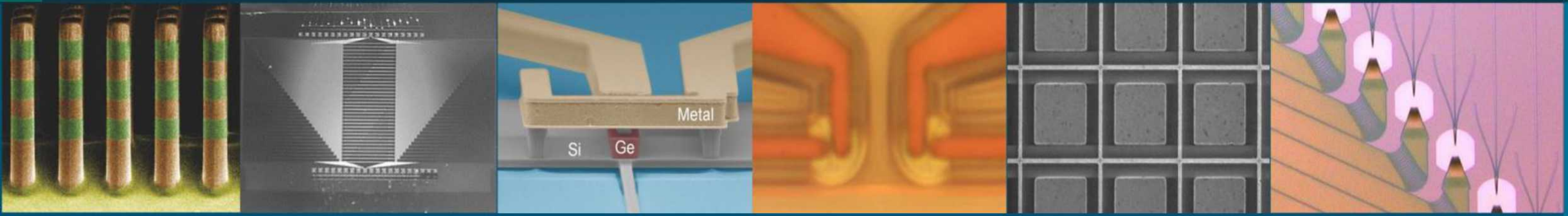
Sandia National Laboratories

SAND2019-5190C

Silicon Photonic Single-Sideband Generation with Dual-Parallel Mach-Zehnder Modulators



PRESENTED BY

Ashok Kodigala, Michael Gehl, Chris T. DeRose, Dana Hood, Andy T. Pomerene, Christina Dallo, Douglas Trotter, Penny Moore, Andrew L. Starbuck, Jongmin Lee, Grant Biedermann, and Anthony L. Lentine

ENERGY NNSA

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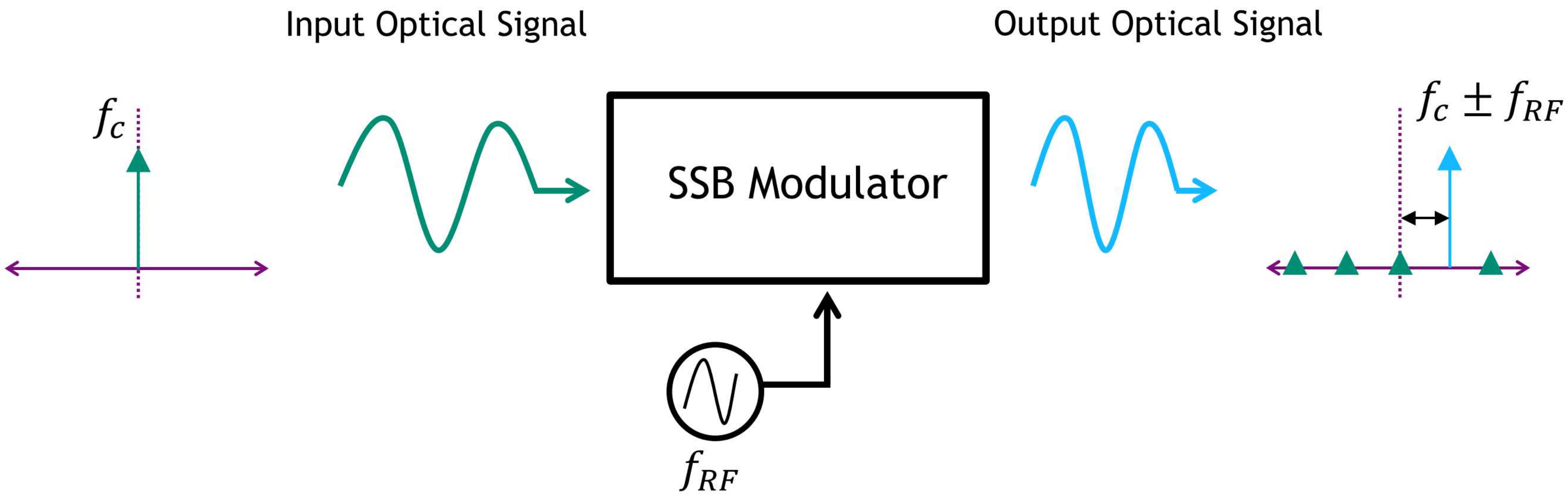
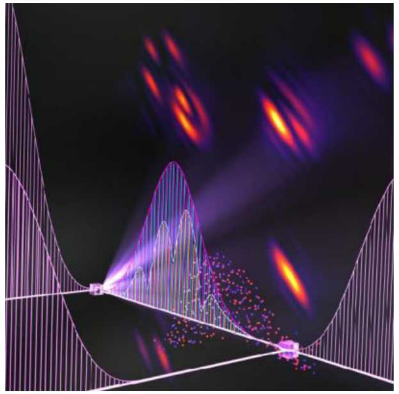
SAND#

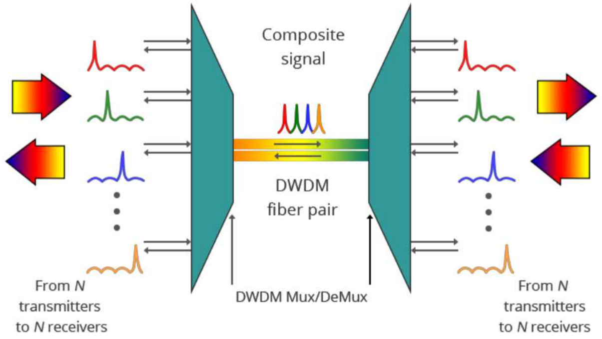
Single-Sideband Modulator





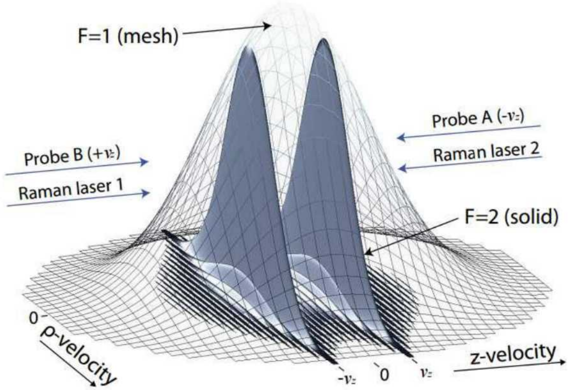
High-Resolution Spectroscopy

Photo credits: Cundiff Laboratory (Univ. of Michigan)



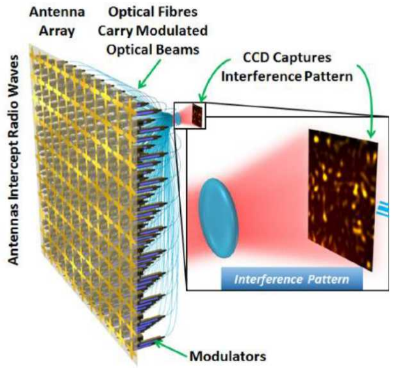
D-WDM Networks

FS.com



Atom Interferometry

Biedermann et al, PRL (2017)



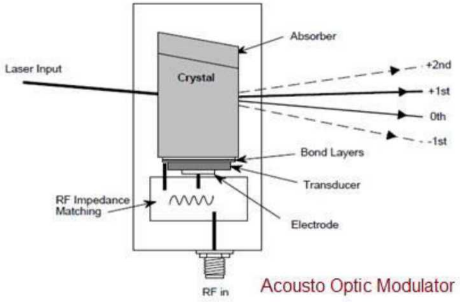
Microwave Photonics

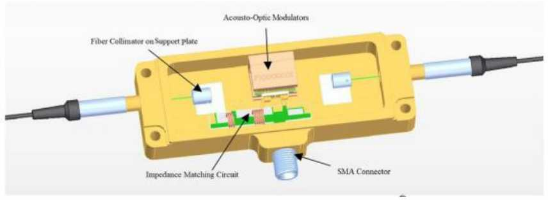
Murakowski et al, Opt. Exp. (2017)

Kodigala et al, CLEO (2019)

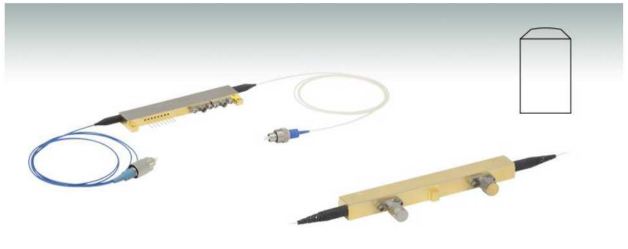
Single-Sideband Modulator

Commercial:



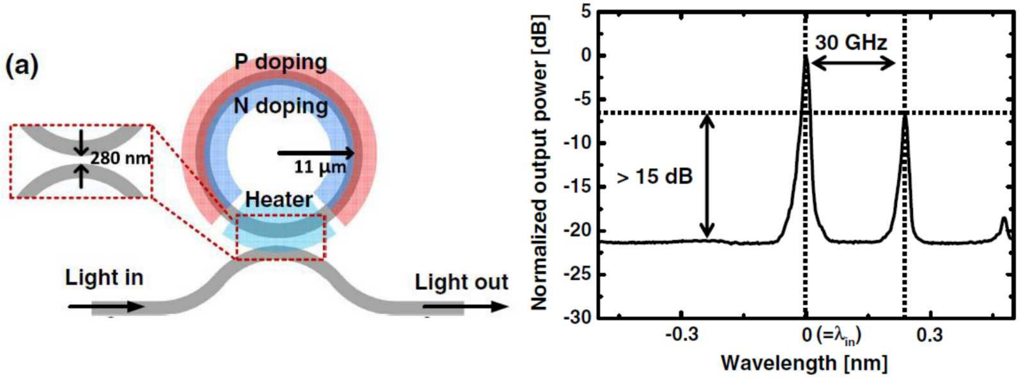


Acousto-optic Modulator (AOMs)



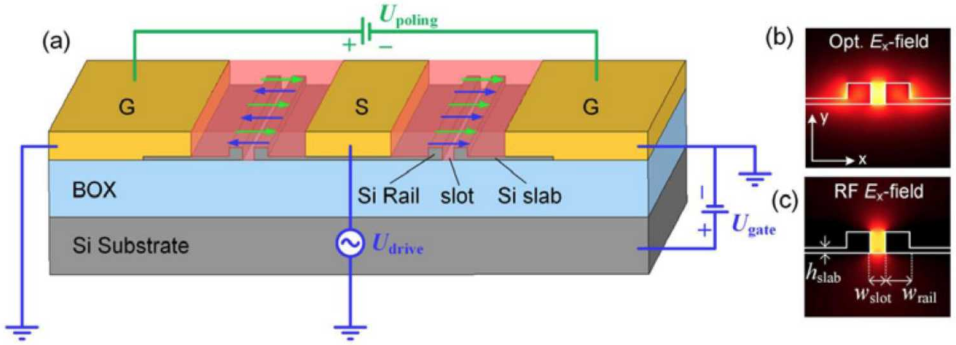
Lithium Niobate (LiNbO3): QPSK (I/Q) modulators

Silicon Photonics:



Yu et al, Phot. Research 6 (2018)

Silicon Ring Modulators



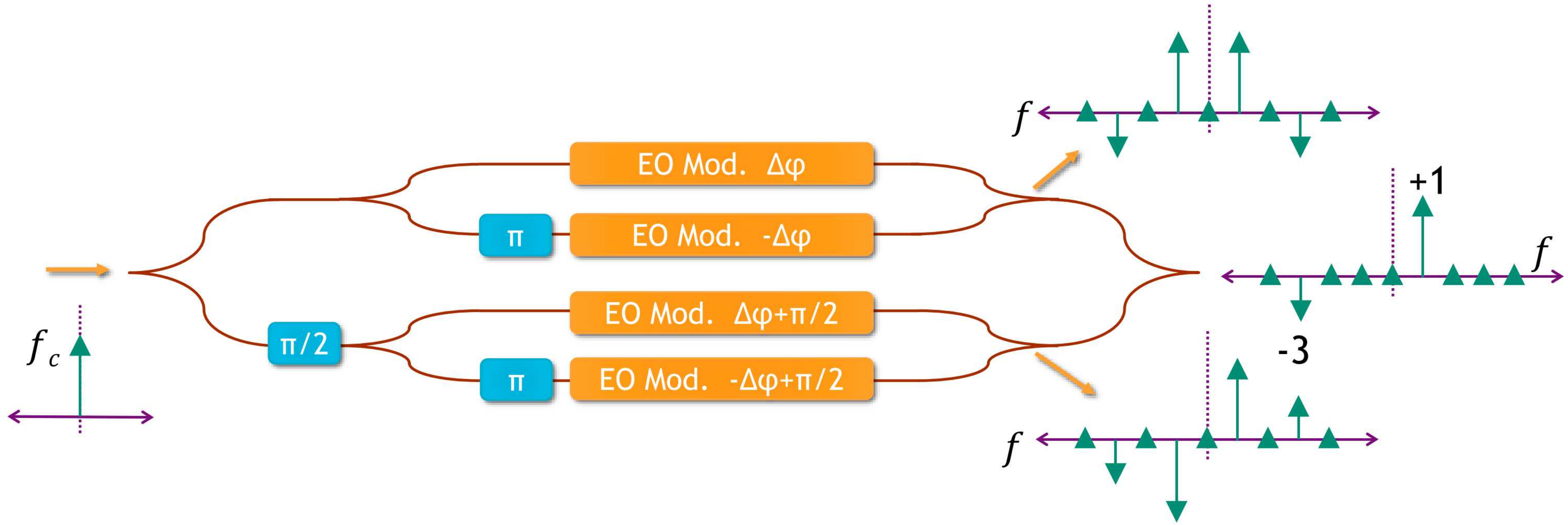
Lauermann et al, Opt. Exp. 24 (2016)

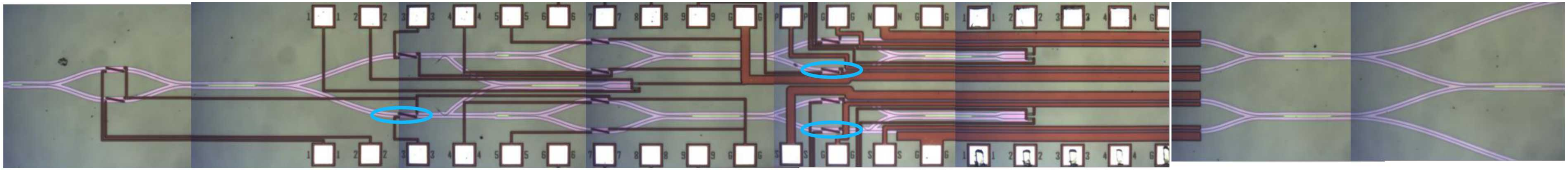
Silicon Organic Hybrid (SOH) SSB Modulator

Photo credits: RFwireless-world.com, Thorlabs.com

Kodigala et al, CLEO (2019)

Dual-parallel MZI



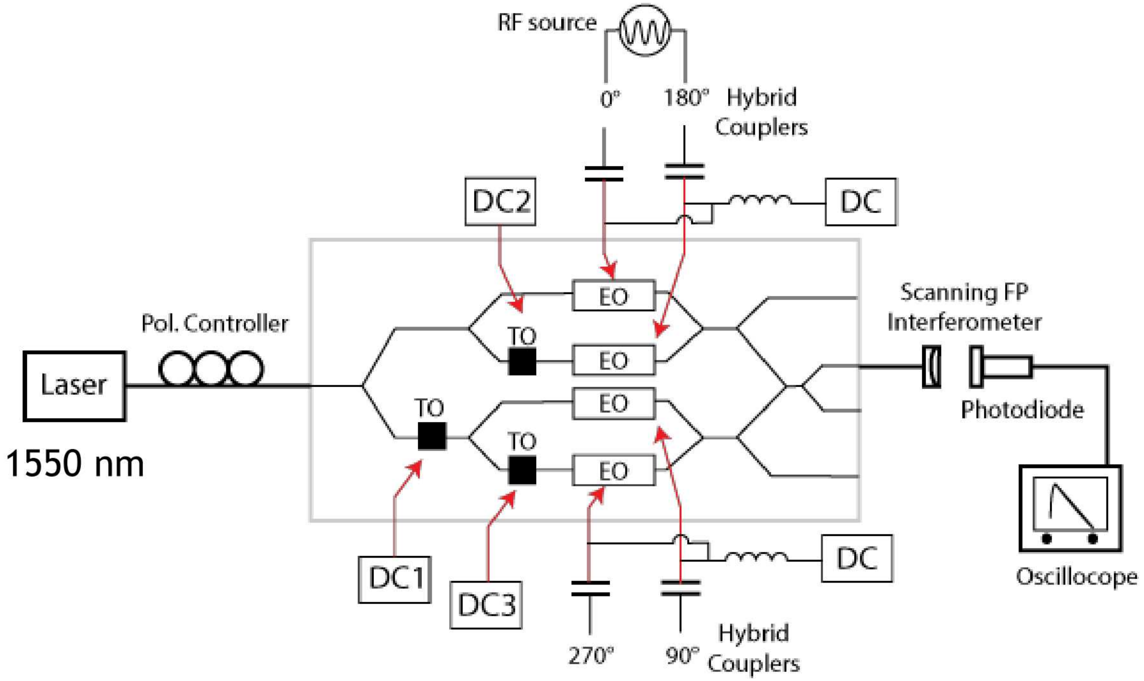


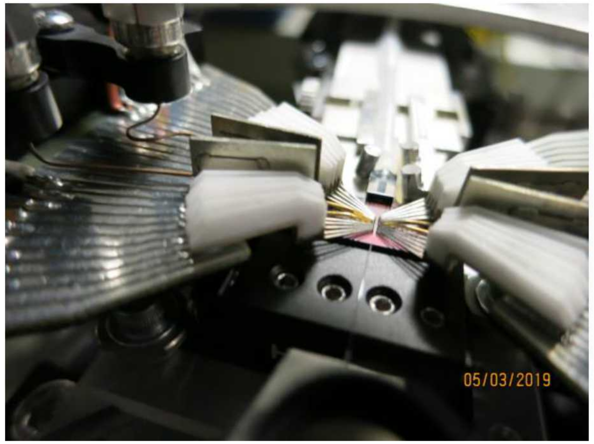
Optical single-sideband (OSSB) modulator fabricated at Sandia National Lab's Silicon Fab

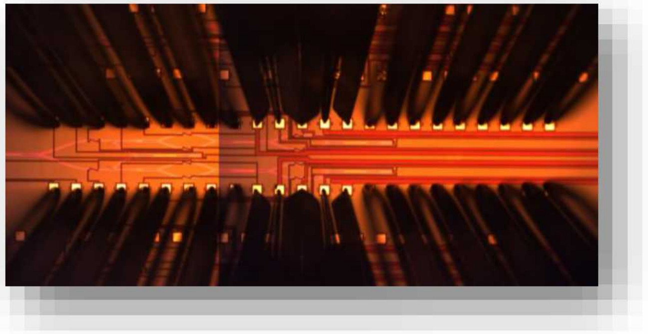
TO phase shifters (blue)
Phase modulators (depletion-mode)
High-contrast MMI splitter

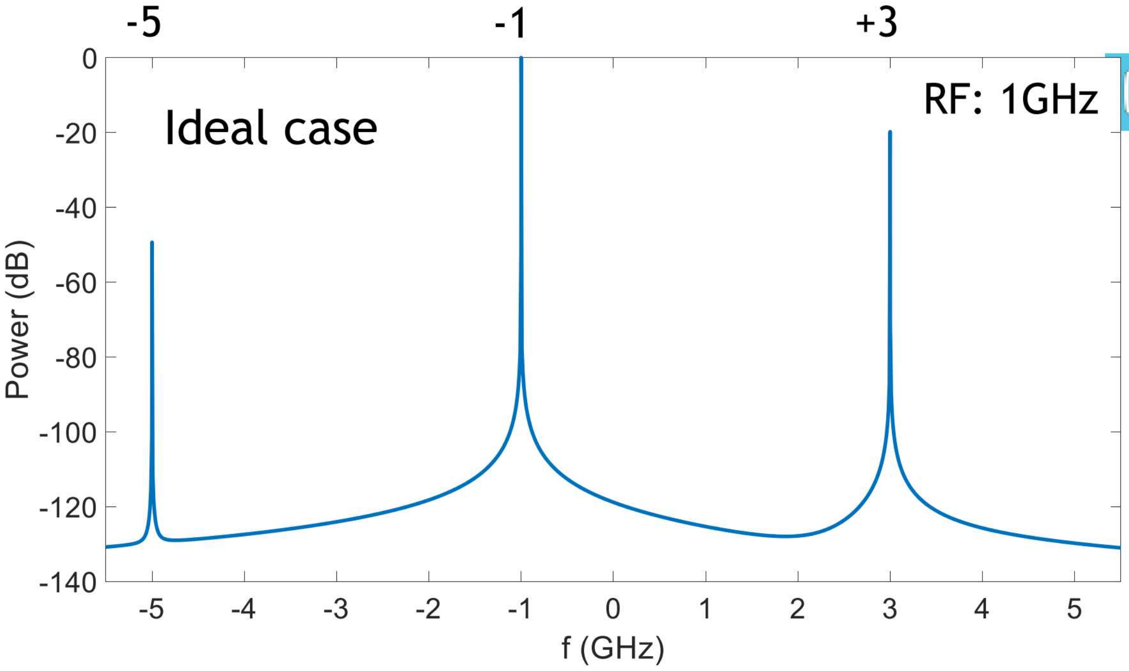
Kodigala et al, CLEO (2019)

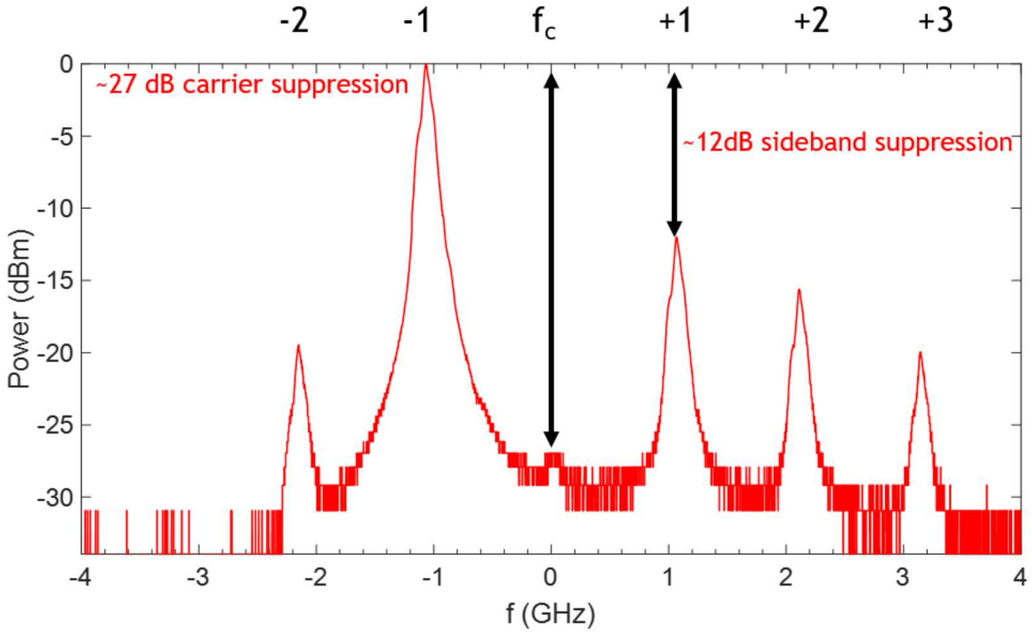
Experimental Setup









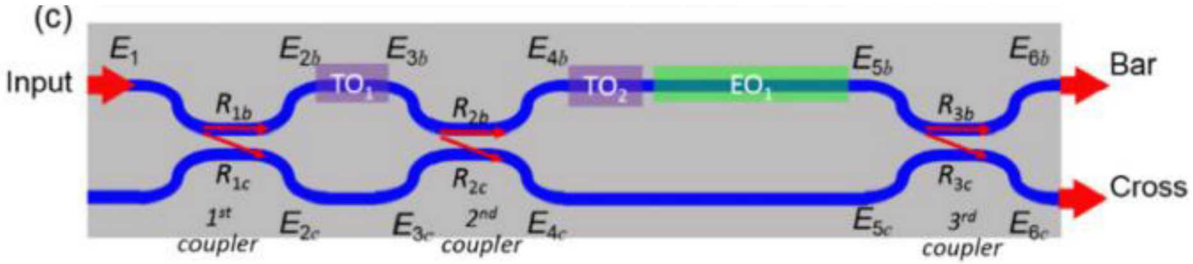


High carrier (27 dB) and sideband suppression (12 dB)

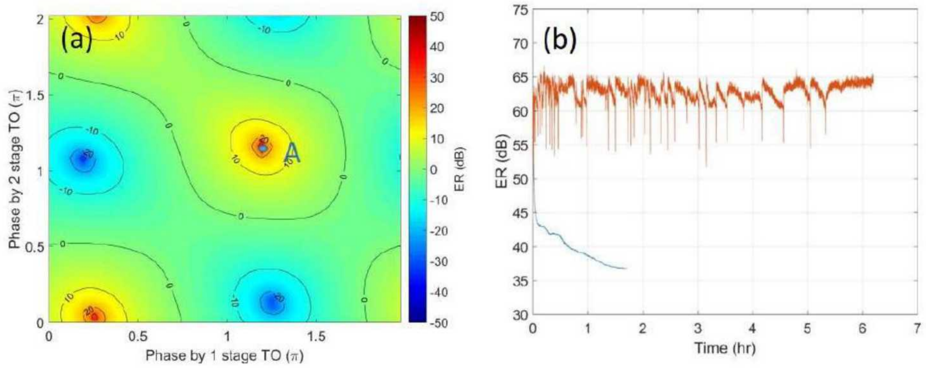
Kodigala et al, CLEO (2019)

High Extinction MZIs

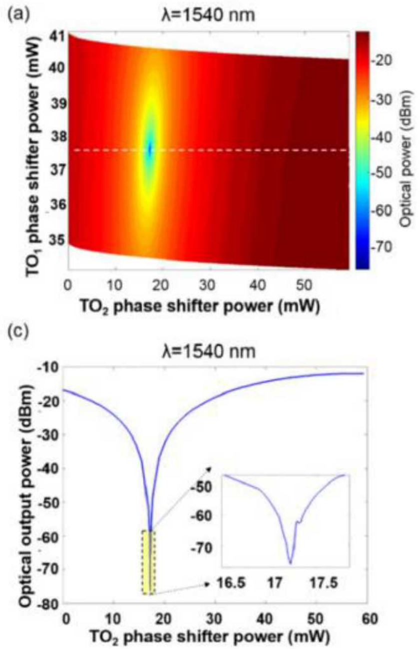
Cascaded MZI (CMZI): High contrast and broadband



S. Lui, et. al. *Opt. Express* **25**, 11254 (2017)



H. Cai et al., OIC (2018)



Extinction: ~60 dB

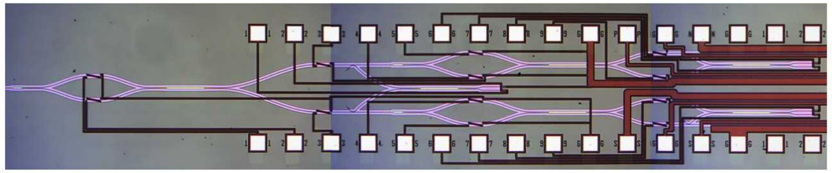
-Biases differ with λ, f_{RF}, thermal crosstalk

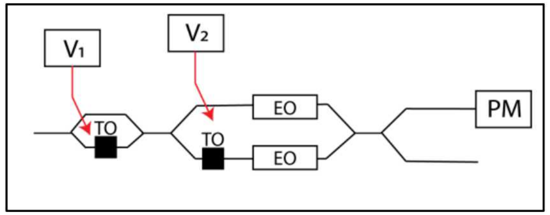
-Drift: Also true for $LiNbO_3$ modulators

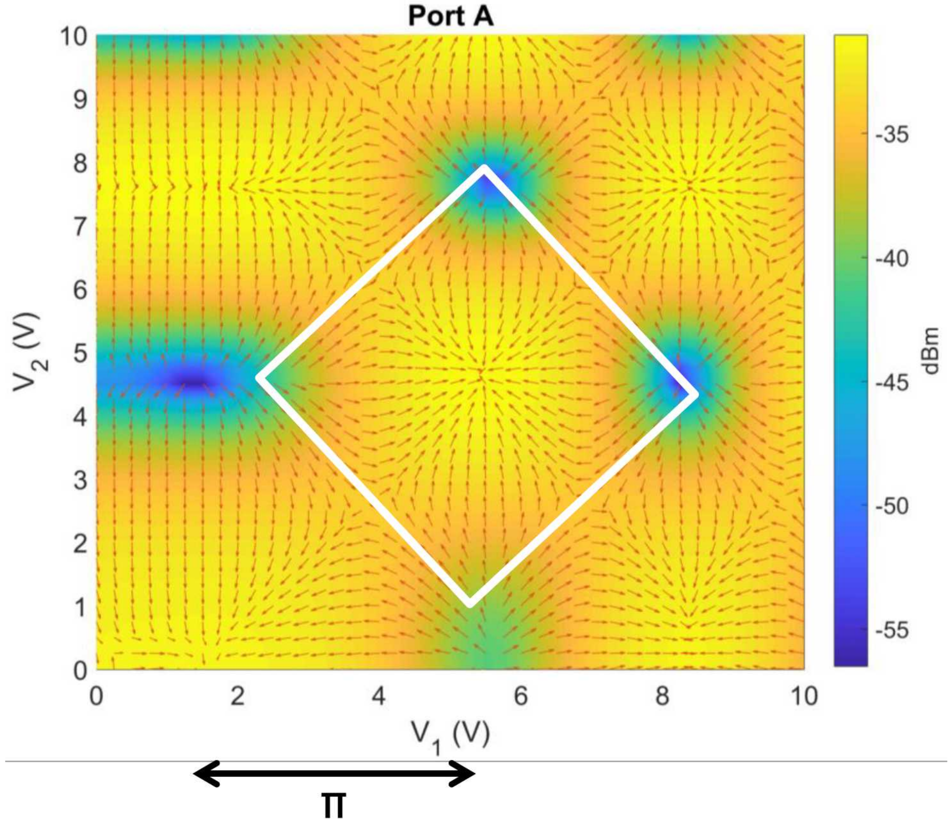
Salvestrini et al, ‘Analysis and control of the DC Drift in $LiNbO_3$-Based Mach-Zehnder Modulators’ JLT **29** (2011)

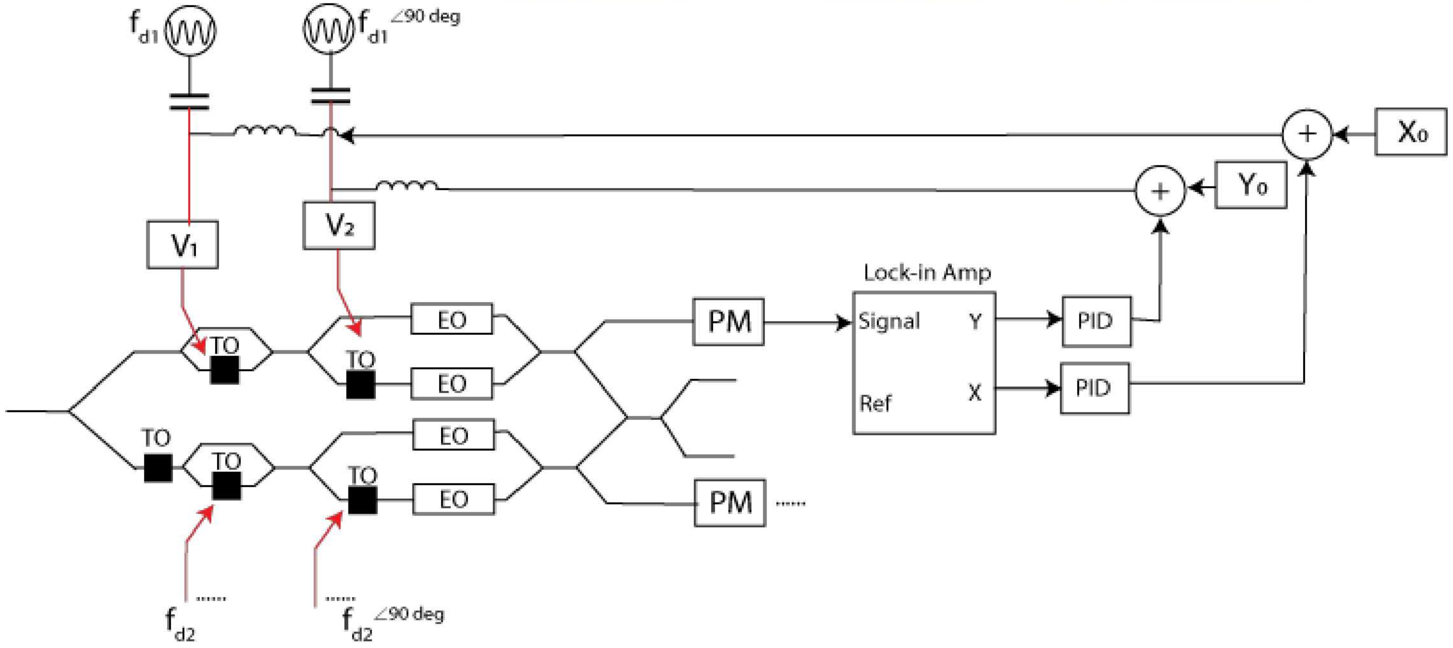
Kodigala et al, CLEO (2019)

Active Feedback





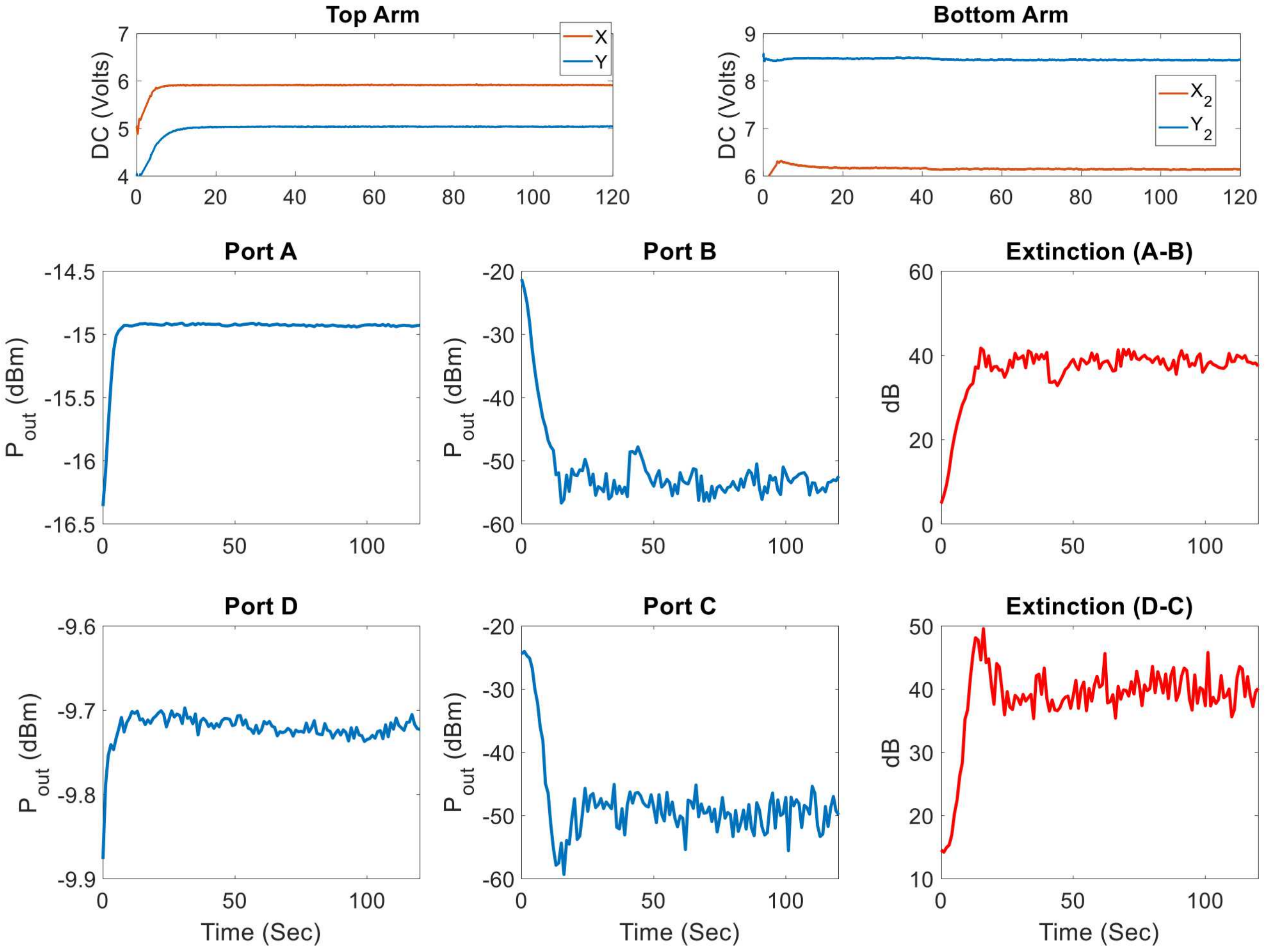




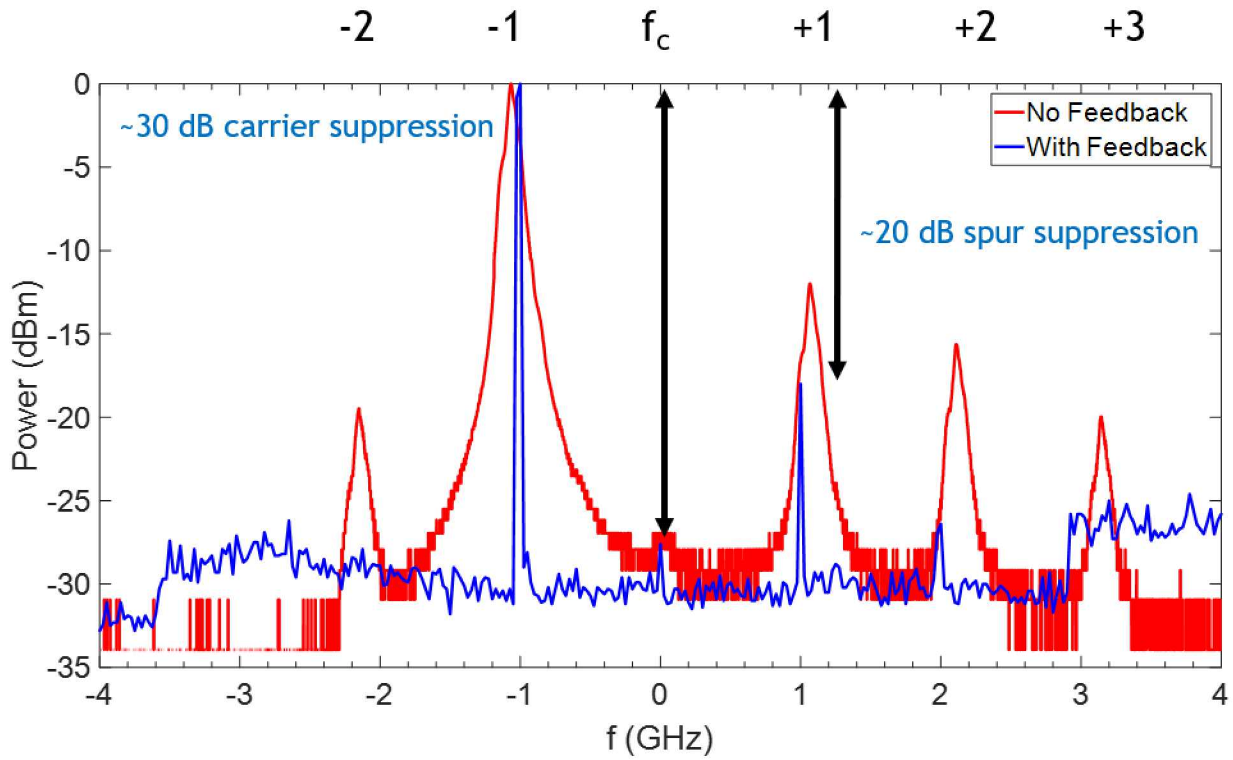
Implemented with DAQ (Simulink)

Kodigala et al, CLEO (2019)

Active Feedback



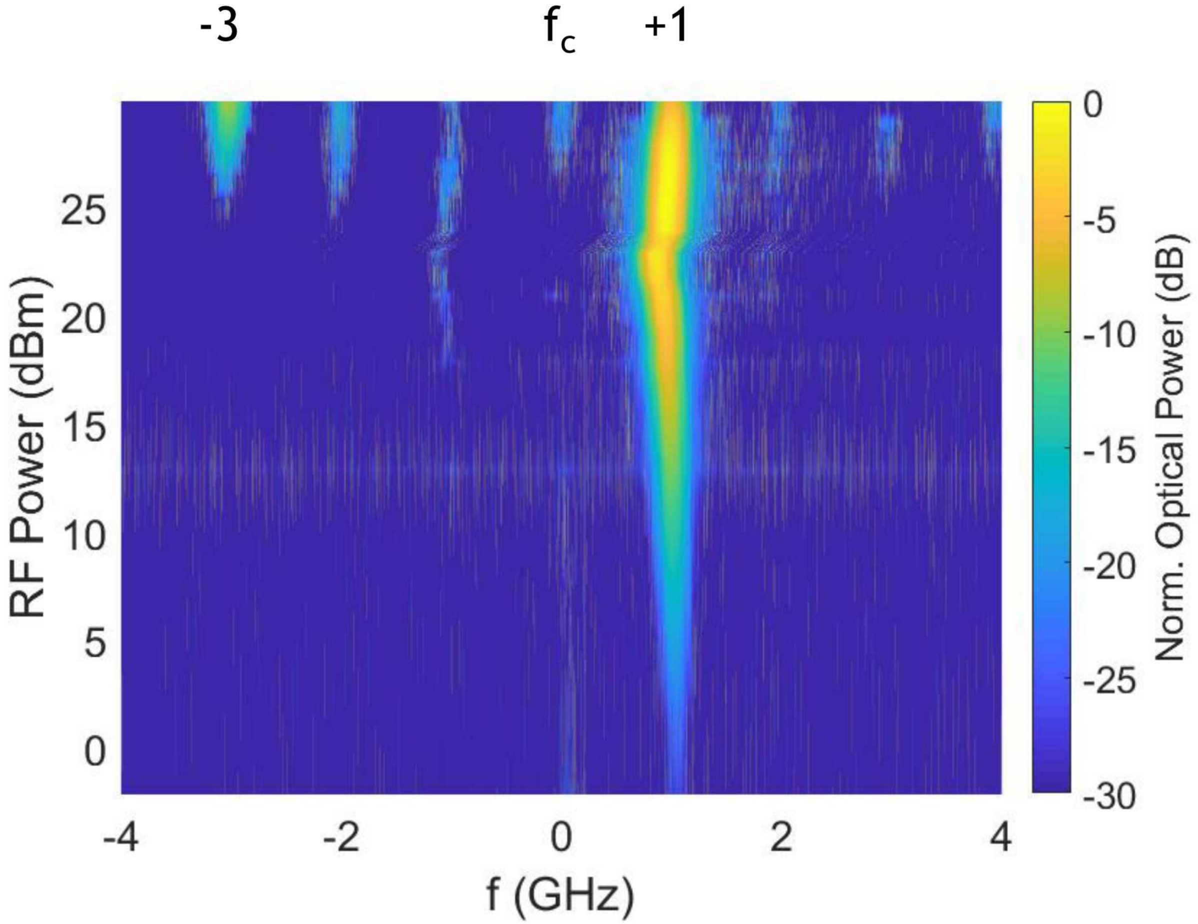
High Extinction: 40 dB (***Self-biased***)

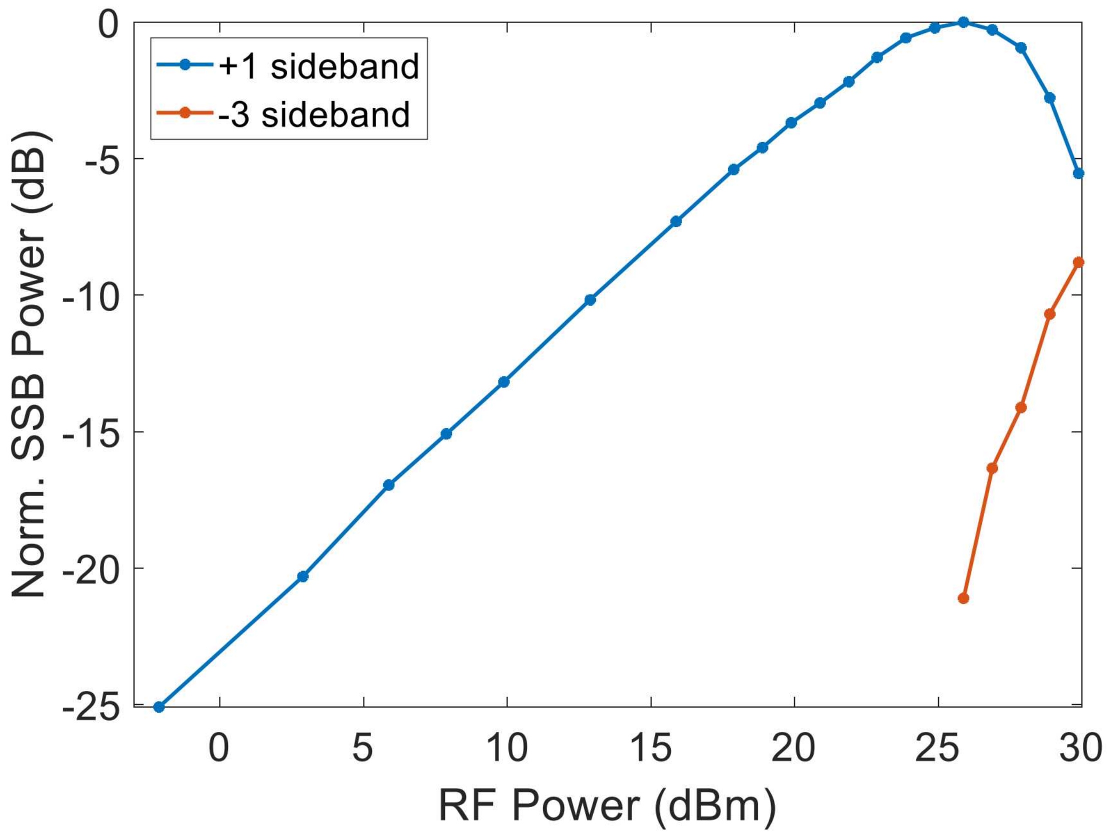


SSB operation with feedback

Kodigala et al, CLEO (2019)

RF Characterization

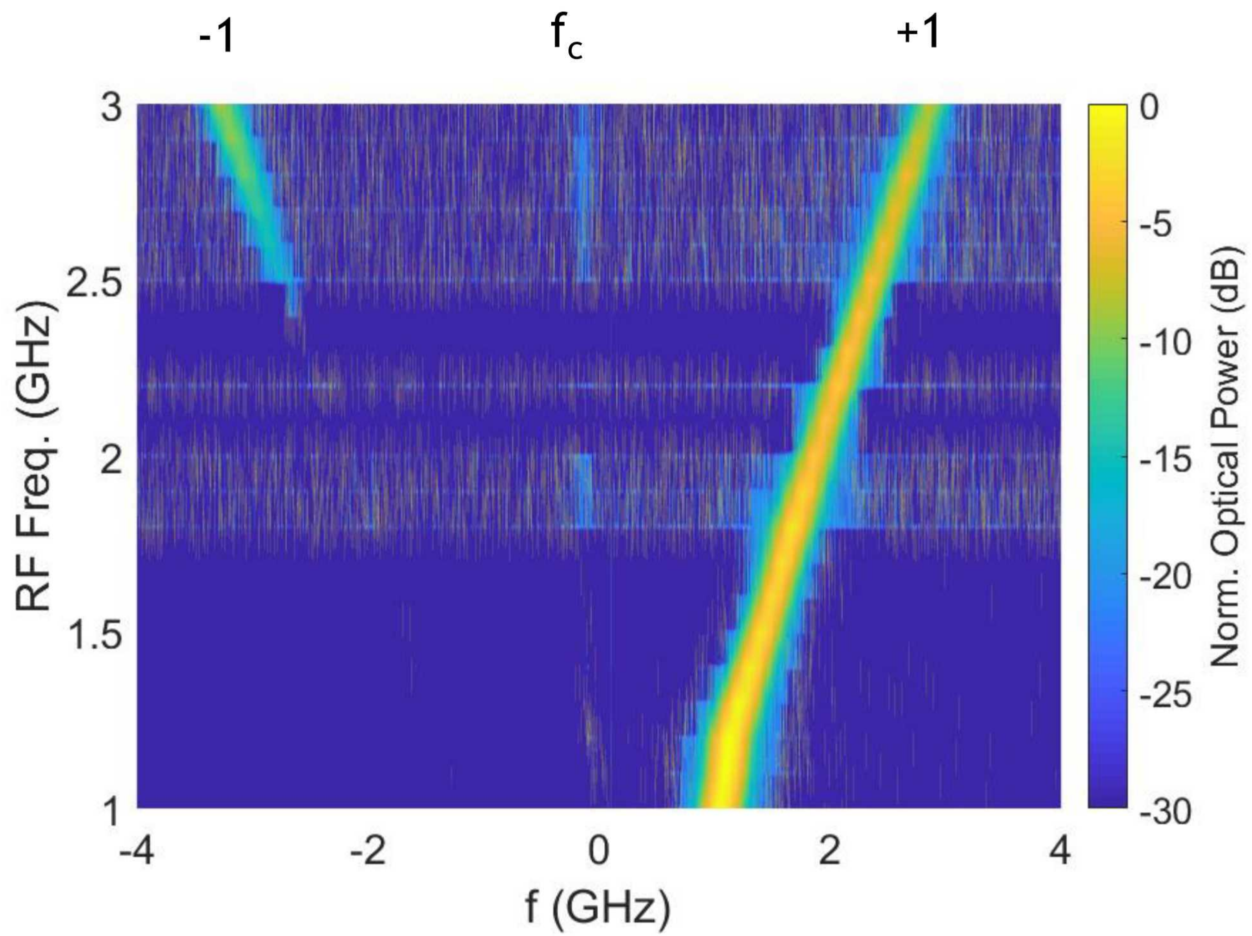


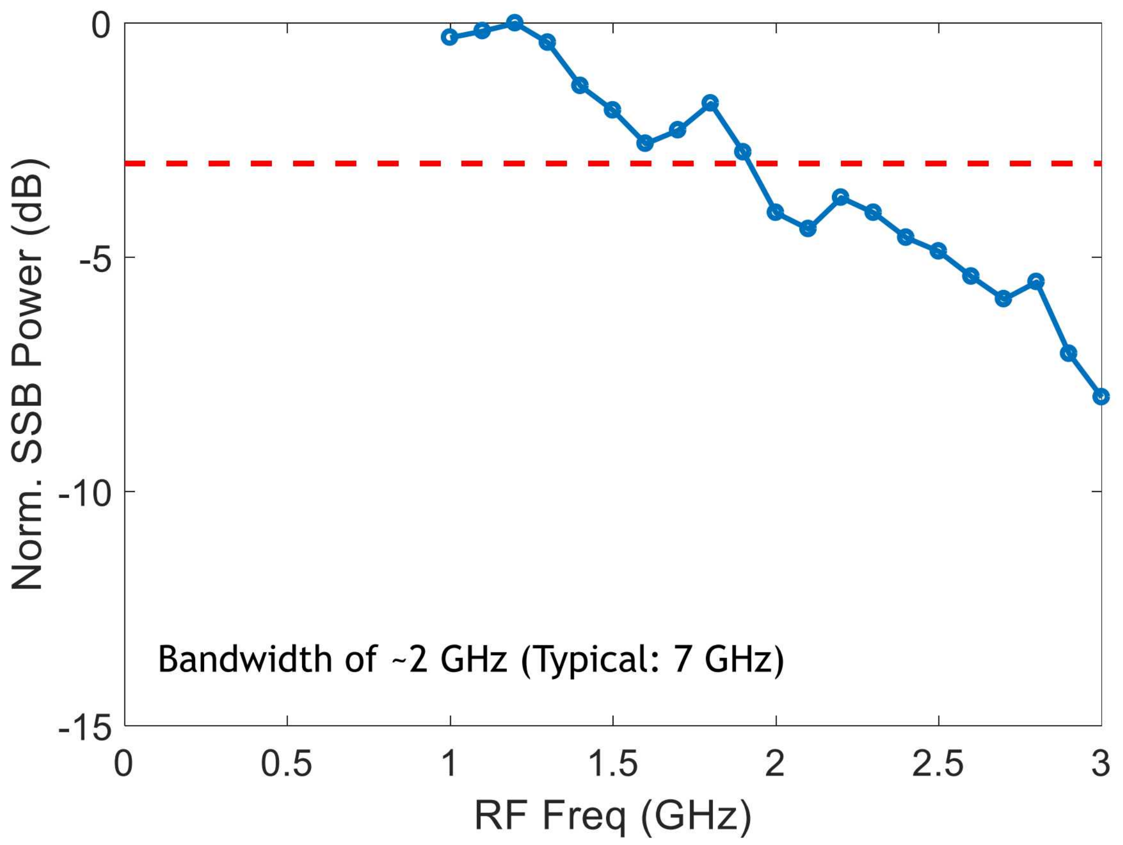


Optimum at RF powers close to ~400mW

Kodigala et al, CLEO (2019)

RF Characterization (Frequency Response)





Traveling Wave Modulator: 24 GHz

C. DeRose, *et. al.*, *Optical Interconnects Conference, IEEE* (2012)

Kodigala et al, CLEO (2019)

Summary

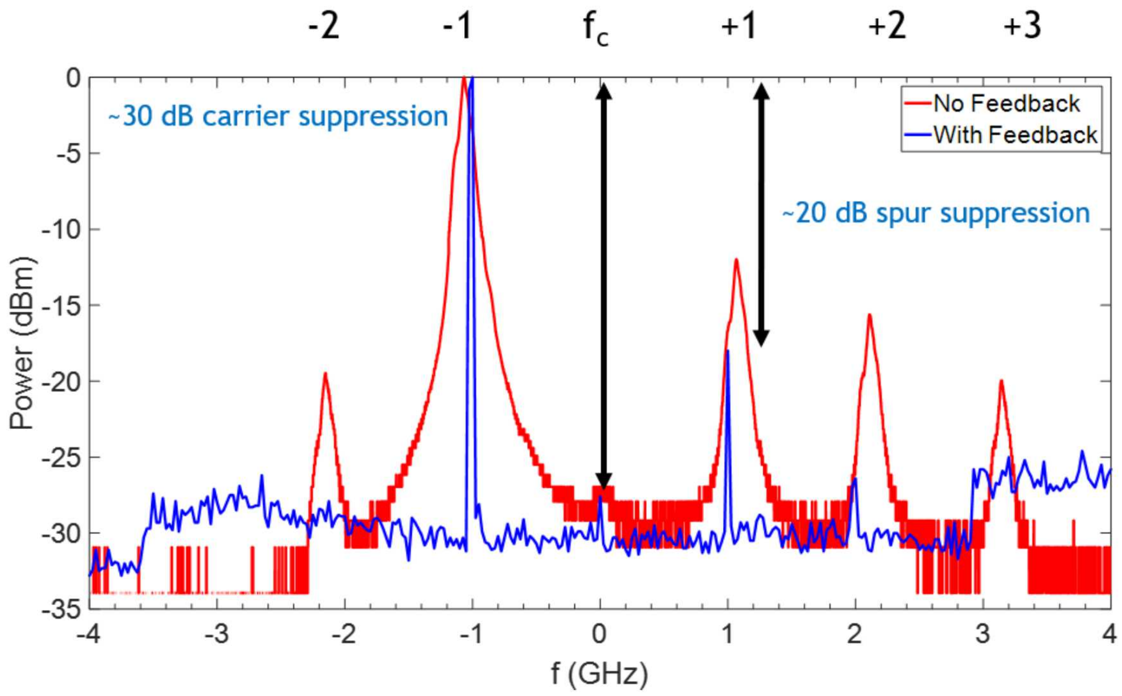
- Integrated silicon CS-SSB modulator (CMOS compatible)

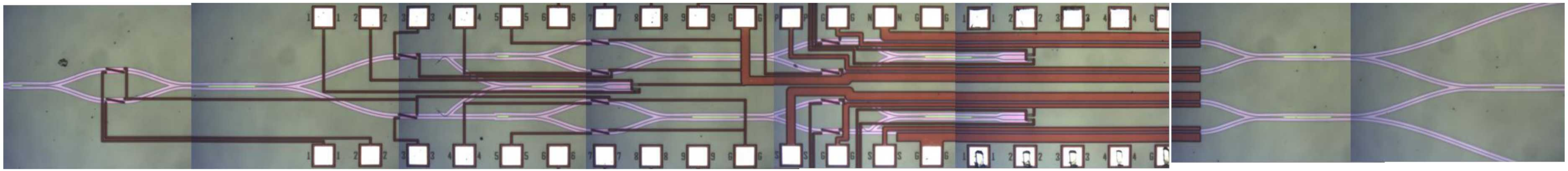
- Active feedback (***Self-biased***):
  - 30 dB carrier suppression
  - >20 unwanted dB sideband suppression

-Current Bandwidth: ~2 GHz
  - Travelling wave design (24 GHz)

-RF Power: ~400 mW

-RF amplitude balancing (improve)





Kodigala et al, CLEO (2019)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Si Waveguide
Avalanche Photodetector
QKD Transceiver
AWG RF Channelizer
IR FPA with ROIC
Photovoltaics with Microlenses
3D Metamaterials
TFLN on Silicon Modulator

Phase Modulation

$$Ae^{i\omega t+i\beta\sin(\Omega t)}$$

If beta is small, Taylor expand to:

$$Ae^{i\omega t}\left(1+i\beta\sin(\Omega t)\right)$$

Two sidebands:

$$Ae^{i\omega t}\left(1+\frac{\beta}{2}\left(e^{i\Omega t}-e^{-i\Omega t}\right)\right)=A\left(e^{i\omega t}+\frac{\beta}{2}e^{i(\omega+\Omega)t}-\frac{\beta}{2}e^{i(\omega-\Omega)t}\right)$$

Jacobi-Anger expansion (All sidebands):

$$Ae^{i\omega t+i\beta\sin(\Omega t)}=Ae^{i\omega t}\left(J_0(\beta)+\sum_{k=1}^{\infty}J_k(\beta)e^{ik\Omega t}+\sum_{k=1}^{\infty}(-1)^k J_k(\beta)e^{-ik\Omega t}\right)$$

Amplitude Modulation (get only 1st sidebands):

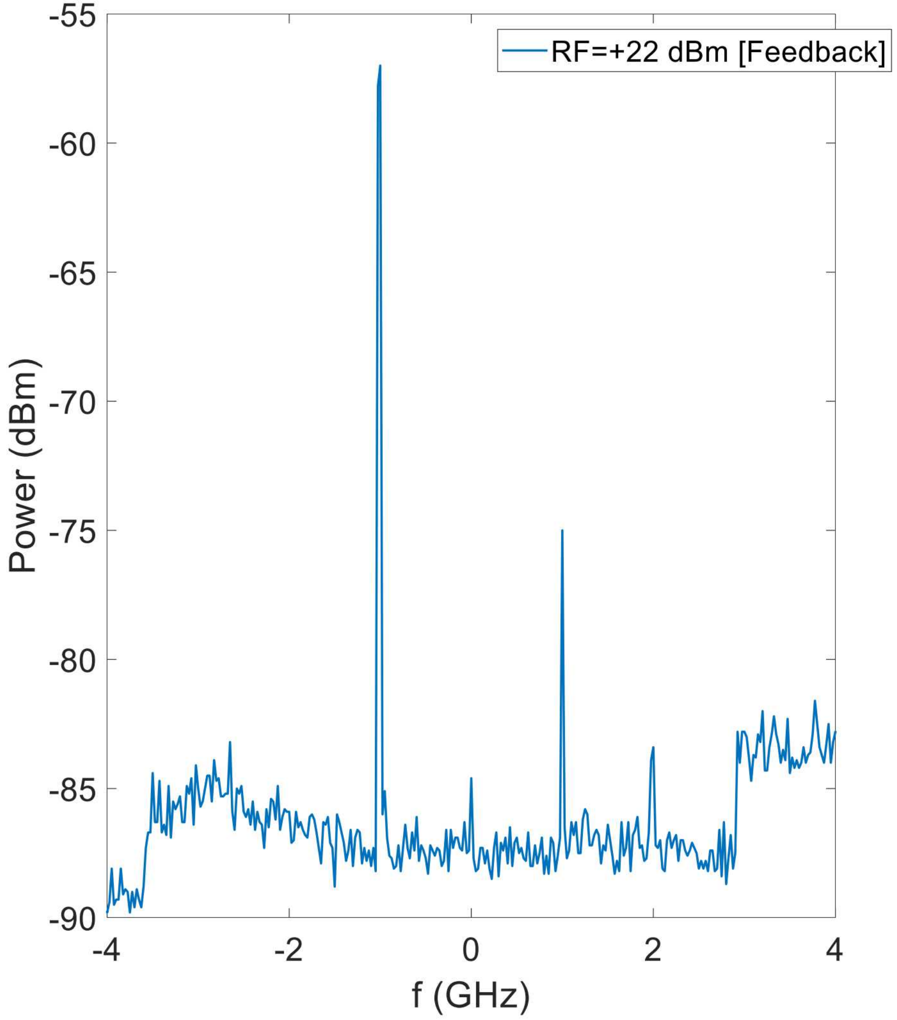
$$\left(1+\beta\sin(\Omega t)\right)Ae^{i\omega t}=Ae^{i\omega t}+\frac{A\beta}{2i}\left(e^{i(\omega+\Omega)t}-e^{i(\omega-\Omega)t}\right)$$

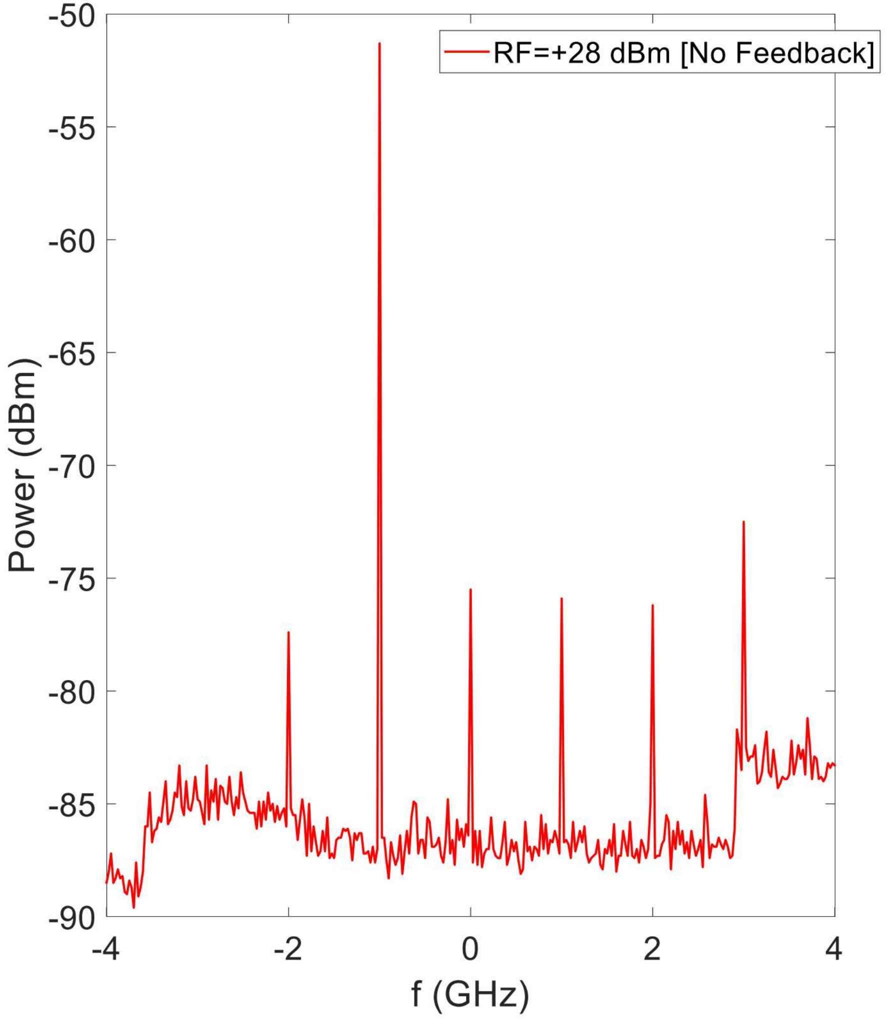
Taylor Series:

$$e^x=\sum_{n=0}^{\infty}\frac{x^n}{n!}=1+x+\frac{x^2}{2!}+\frac{x^3}{3!}+\frac{x^4}{4!}+\cdots.$$

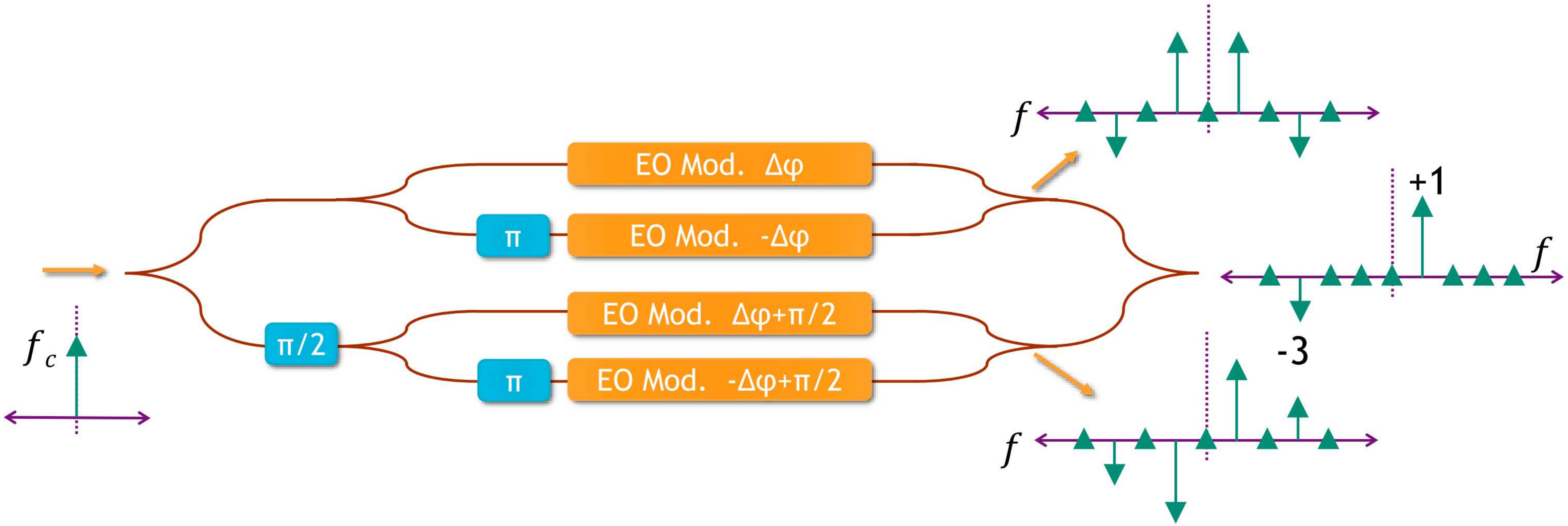
Kodigala et al, CLEO (2019)

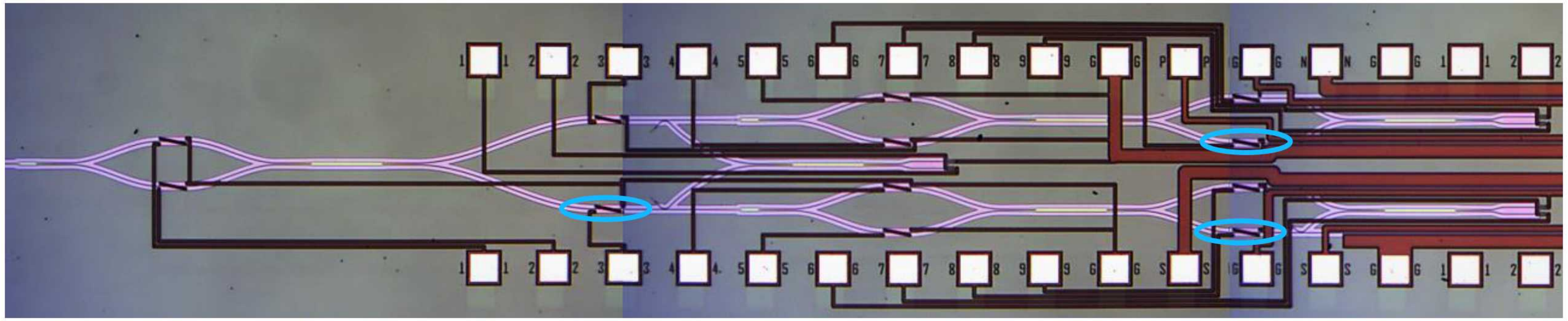
Heterodyne detection (w/ RF amp)





Dual-parallel MZI





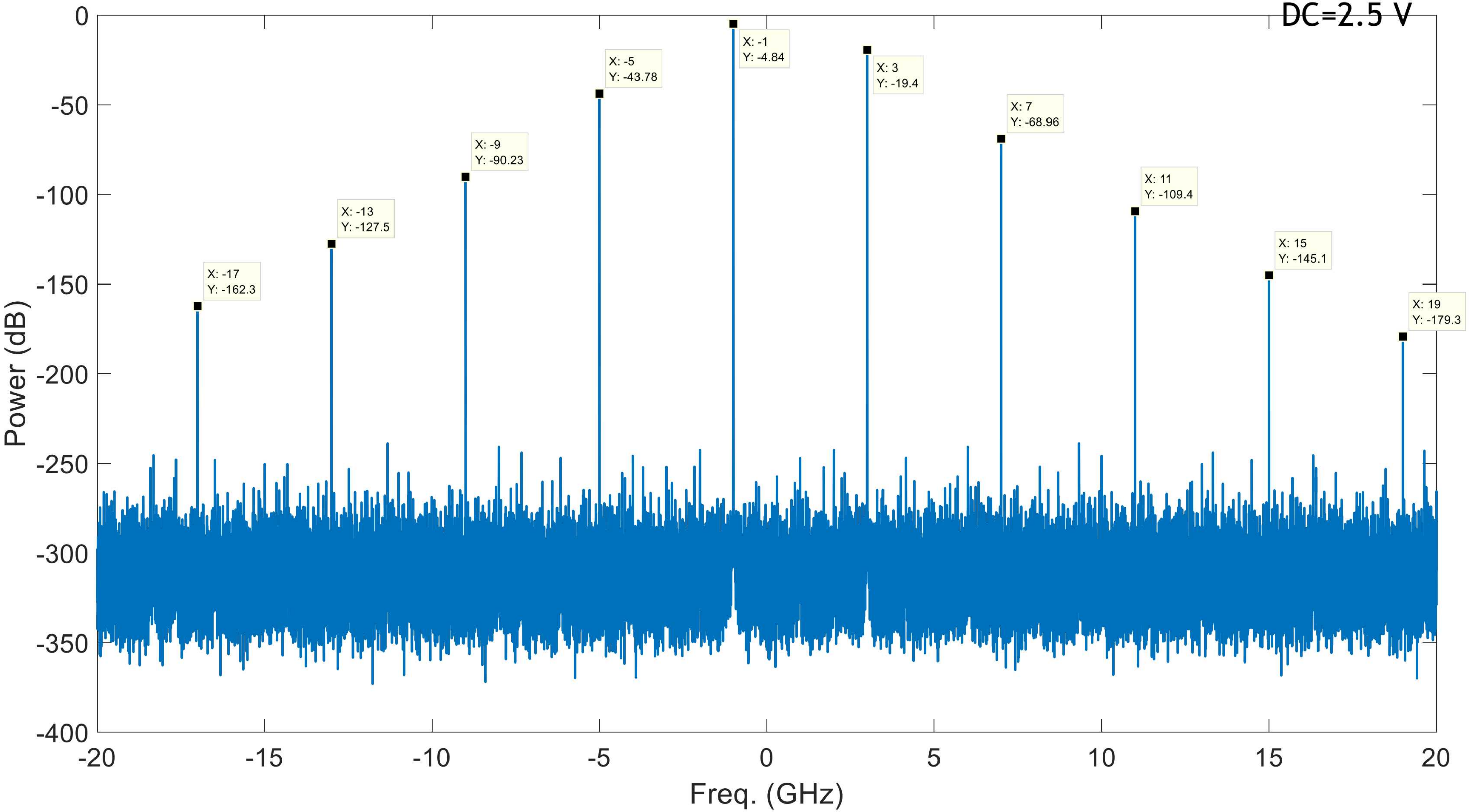
Optical single-sideband (OSSB) modulator fabricated at Sandia National Labs (Silicon Fab)

TO phase shifters (blue)
Phase modulators (depletion-mode)

Kodigala et al, CLEO (2019)

Modeling (non-linear index model)

0 dB input
Mod=2.46 V
DC=2.5 V



Modeling (non-linear index model)

RF Phases

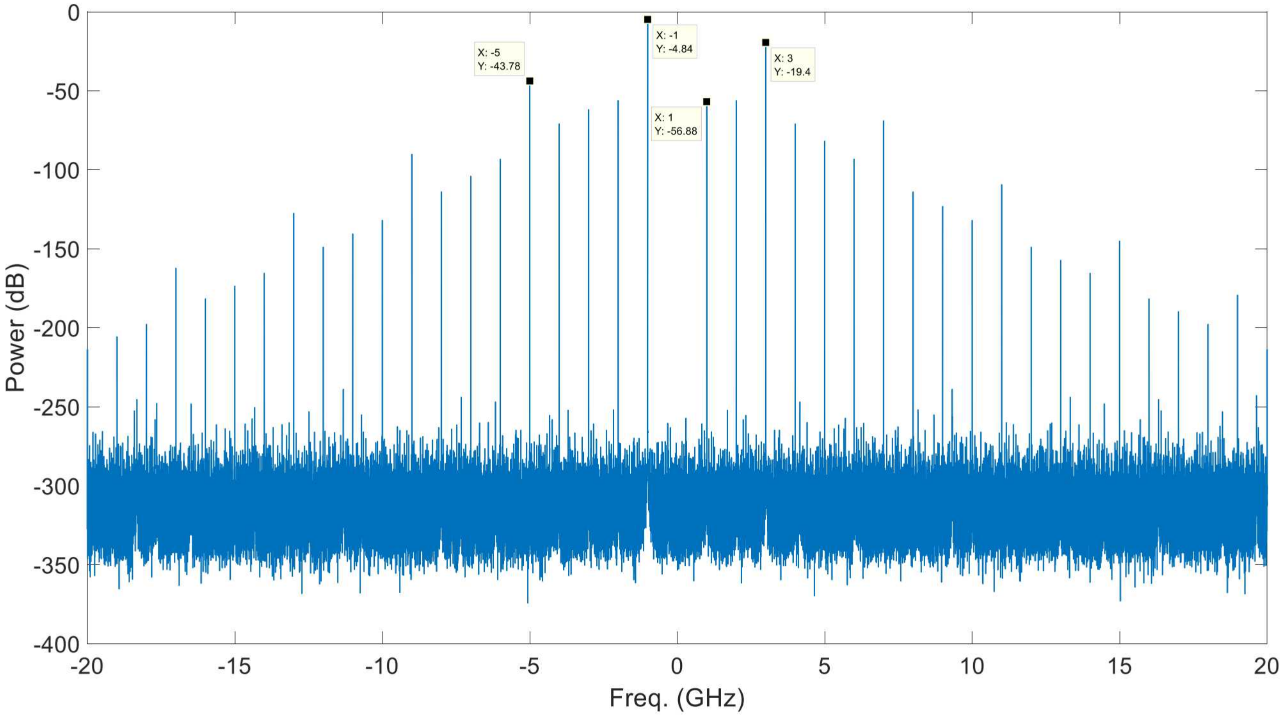
$\Phi_a=0$
$\Phi_b=\pi/2$

$\Phi_1=0$
$\Phi_2=\pi$
$\Phi_3=0$
$\Phi_4=\pi$

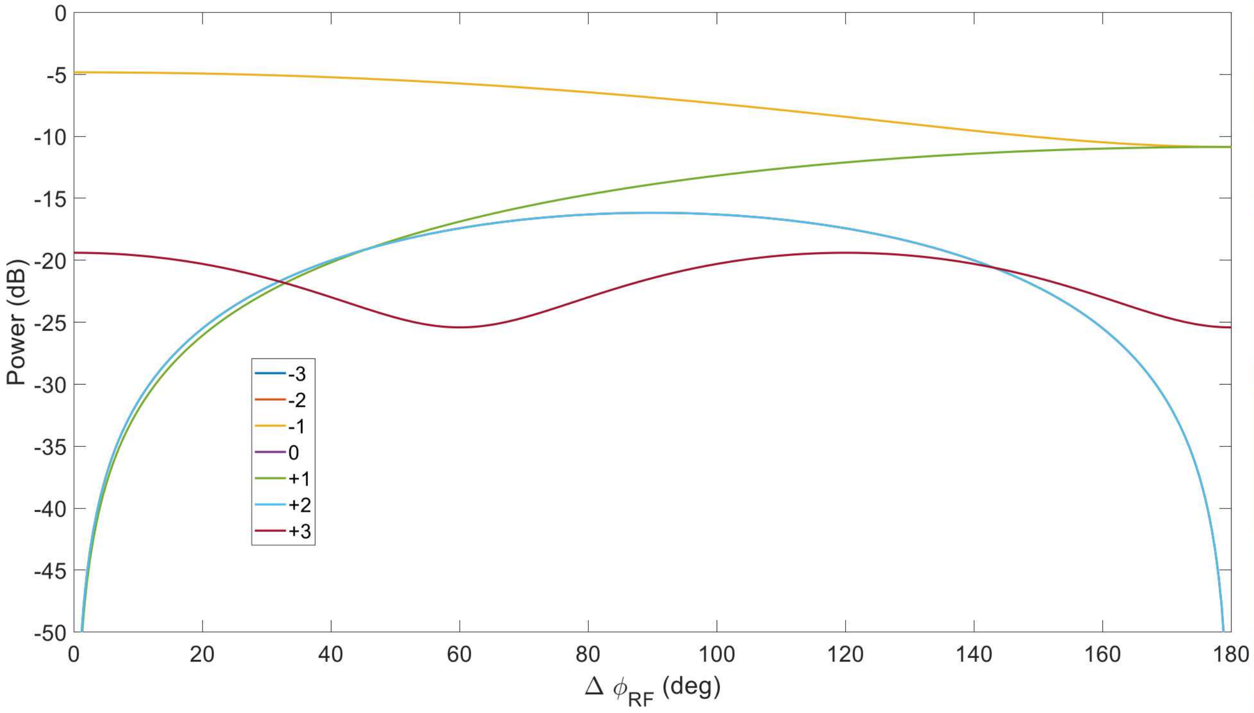
$\varphi_{1RF}=0$
$\varphi_{2RF}=\pi$
$\varphi_{3RF}=\pi/2$
$\varphi_{4RF}=3\pi/2$

Pin=0 dB input
Mod=2.46 V
DC=2.5 V

$\Delta\varphi_{1RF}$ =0.01 rad (0.57 deg)



$\Delta\varphi_{RF}$ =sweep



Any single RF phase needs to be ~30 deg off for +/-2,+1 to grow pasts +3

RF phase has no effect on carrier suppression

Modeling (non-linear index model)

$\Phi_a=0$ $\Phi_b=\pi/2$

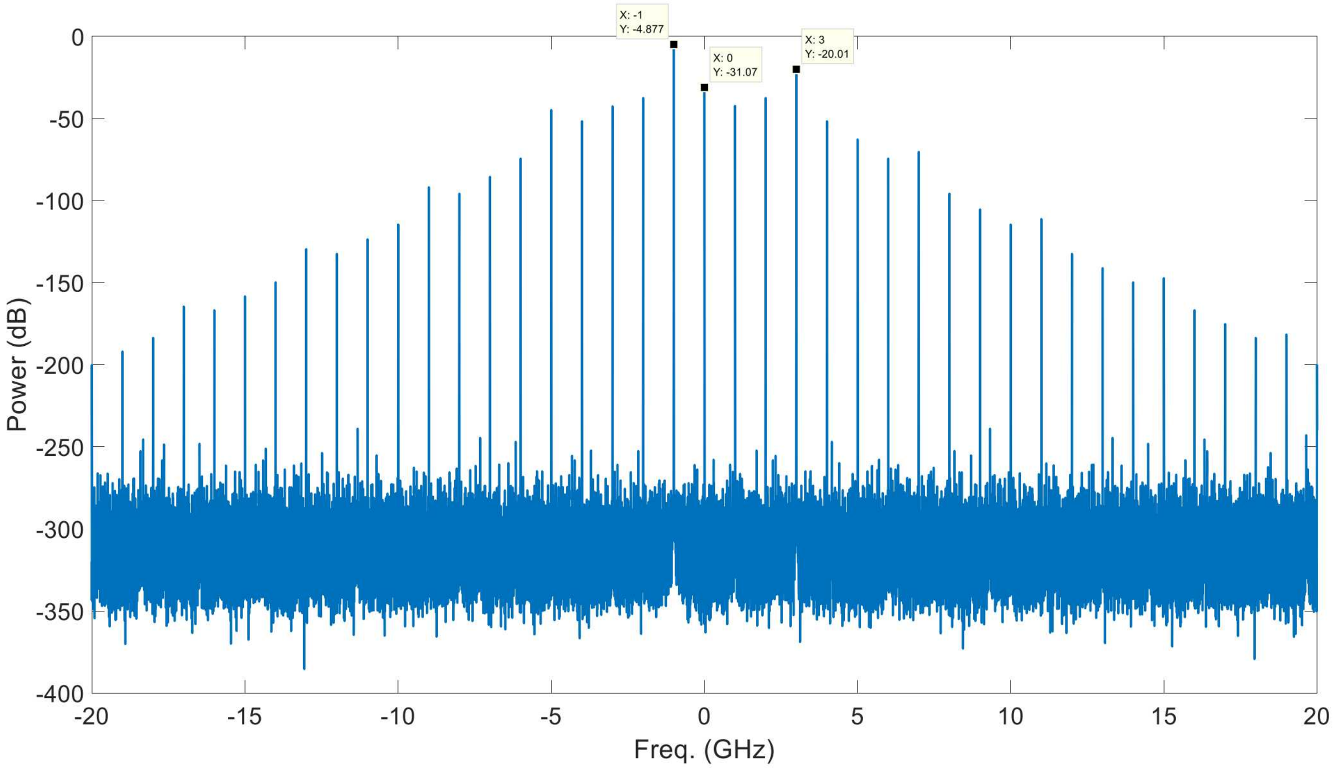
$\Phi_1=0$ $\Phi_2=\pi$ $\Phi_3=0$ $\Phi_4=\pi$

$\varphi_{1RF}=0$ $\varphi_{2RF}=\pi$ $\varphi_{3RF}=\pi/2$ $\varphi_{4RF}=3\pi/2$

Pin=0 dB input
Mod=2.46 V
DC=2.5 V

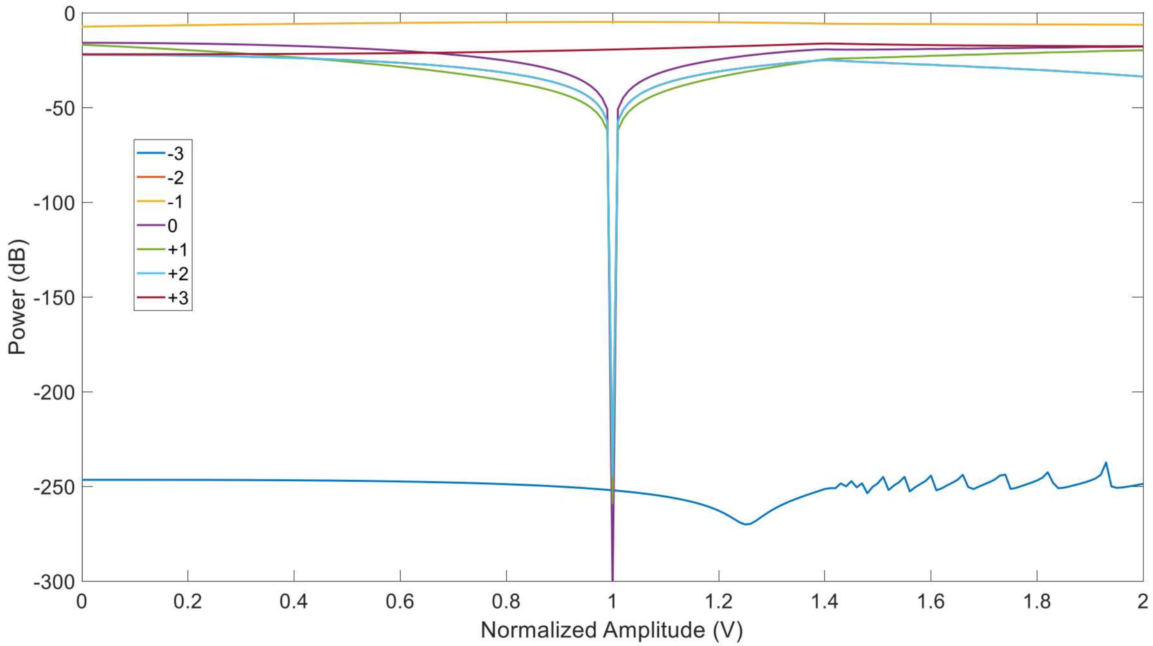
RF amplitude

V_{1RF} =0.9 (90% of the other); Va=2.46 V



25 dB carrier suppression relative to -1 sideband

Va=2.46 V



RF amplitude imbalance will reduce carrier suppression and introduce sidebands (need to be within 0.3dB RF power for <35 dB carrier suppression)

Modeling (non-linear index model)

Optical Phases

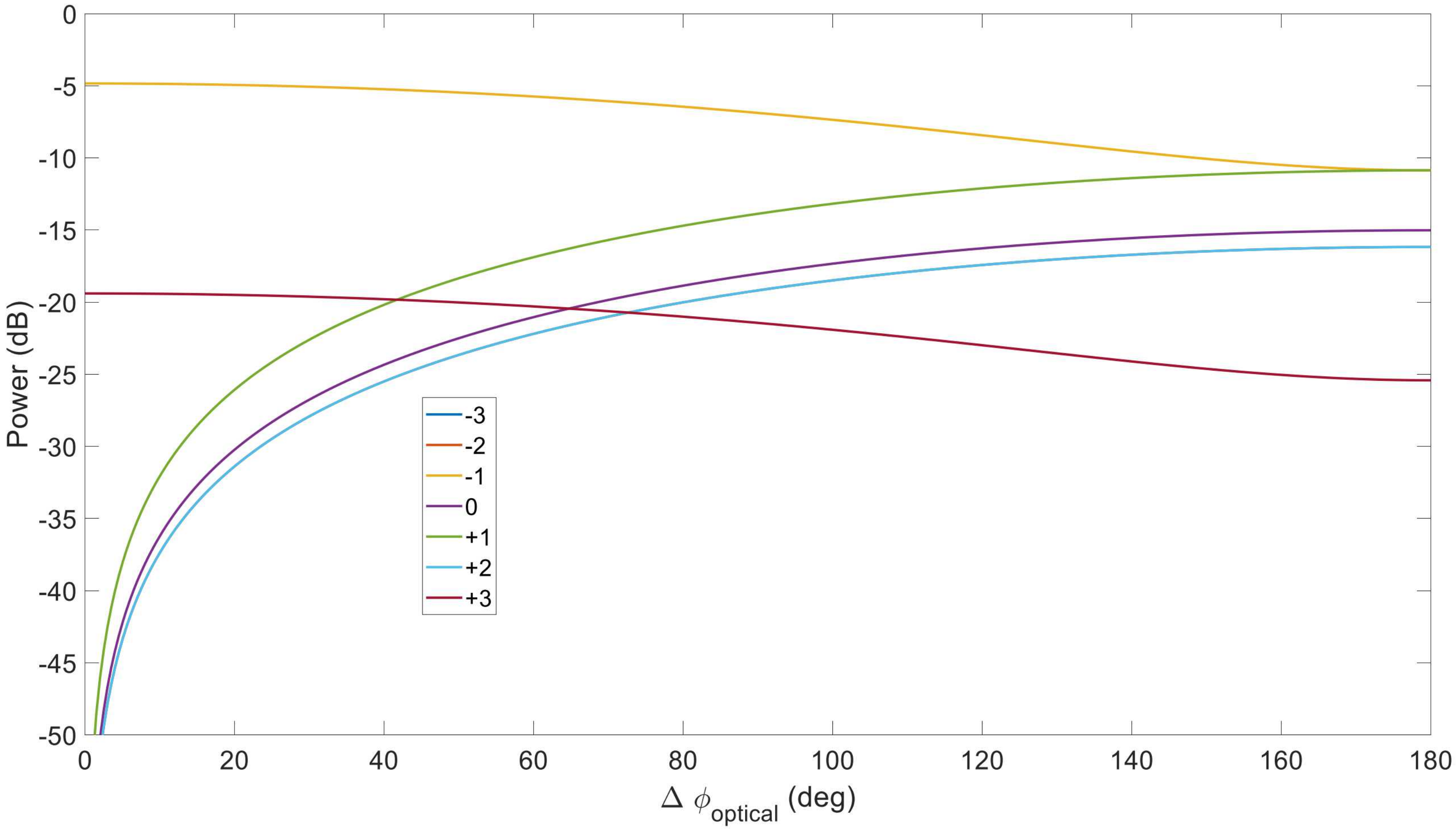
$\Phi_a=0$
$\Phi_b=\pi/2$

$\Phi_1=0$
$\Phi_2=\pi$
$\Phi_3=0$
$\Phi_4=\pi$

$\varphi_{1RF}=0$
$\varphi_{2RF}=\pi$
$\varphi_{3RF}=\pi/2$
$\varphi_{4RF}=3\pi/2$

Pin=0 dB input
Mod=2.46 V
DC=2.5 V

$\Delta\ \Phi_{optical}$ =sweep (1-4)



Any single optical phase offset has an adverse effect on carrier suppression and sideband suppression (tolerance: ~<10 deg)

Modeling (non-linear index model)

Modulation Amplitude vs Bias

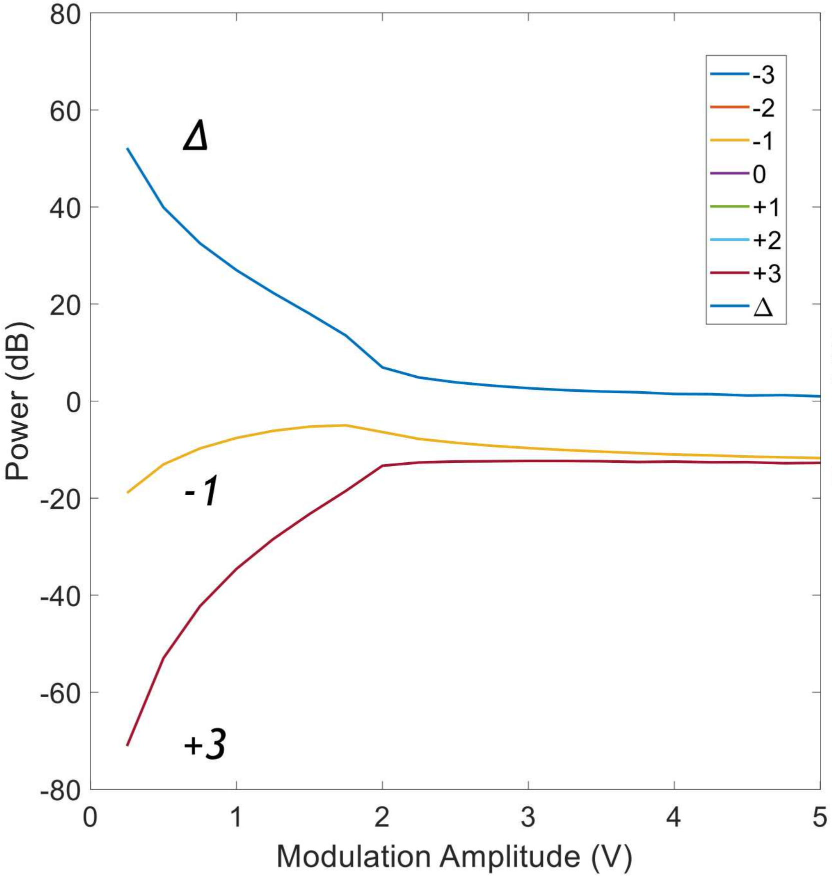
$\Phi_a=0$
$\Phi_b=\pi/2$

$\Phi_1=0$
$\Phi_2=\pi$
$\Phi_3=0$
$\Phi_4=\pi$

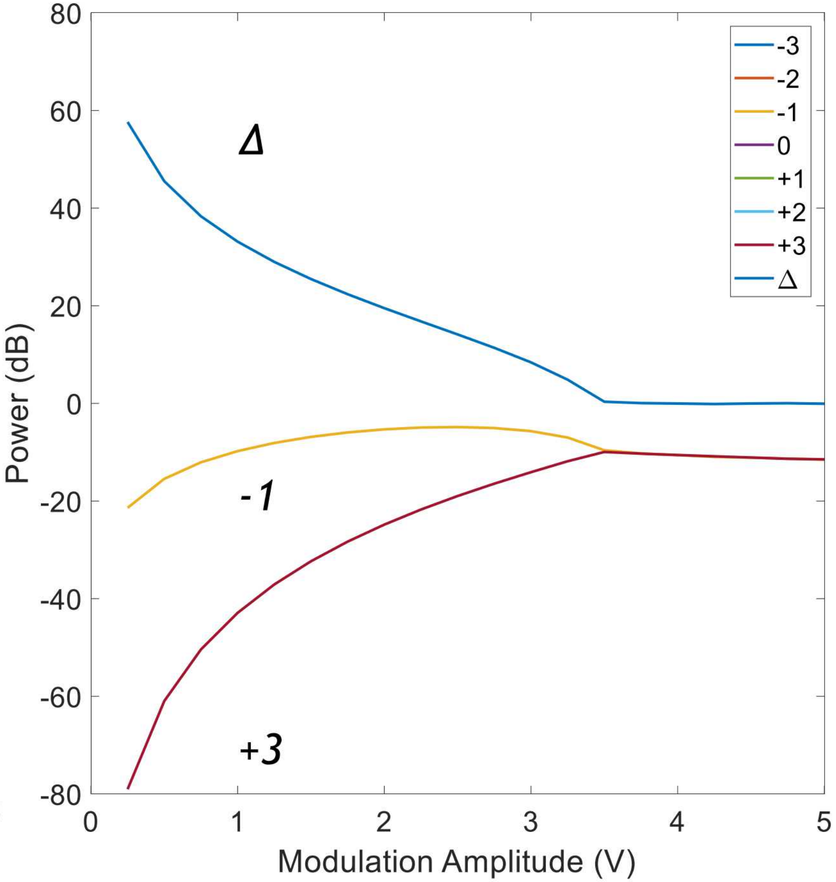
$\varphi_{1RF}=0$
$\varphi_{2RF}=\pi$
$\varphi_{3RF}=\pi/2$
$\varphi_{4RF}=3\pi/2$

Pin=0 dB input
Mod_{RF}=SWEEP
DC=vary

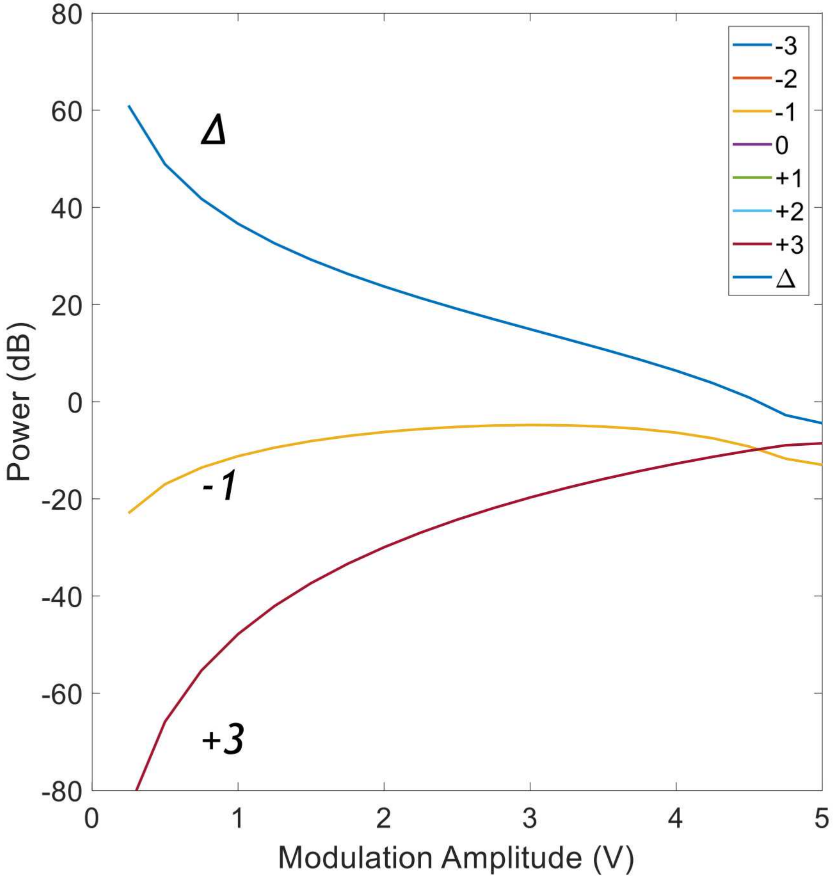
DC=-1 V



DC=-2.5 V

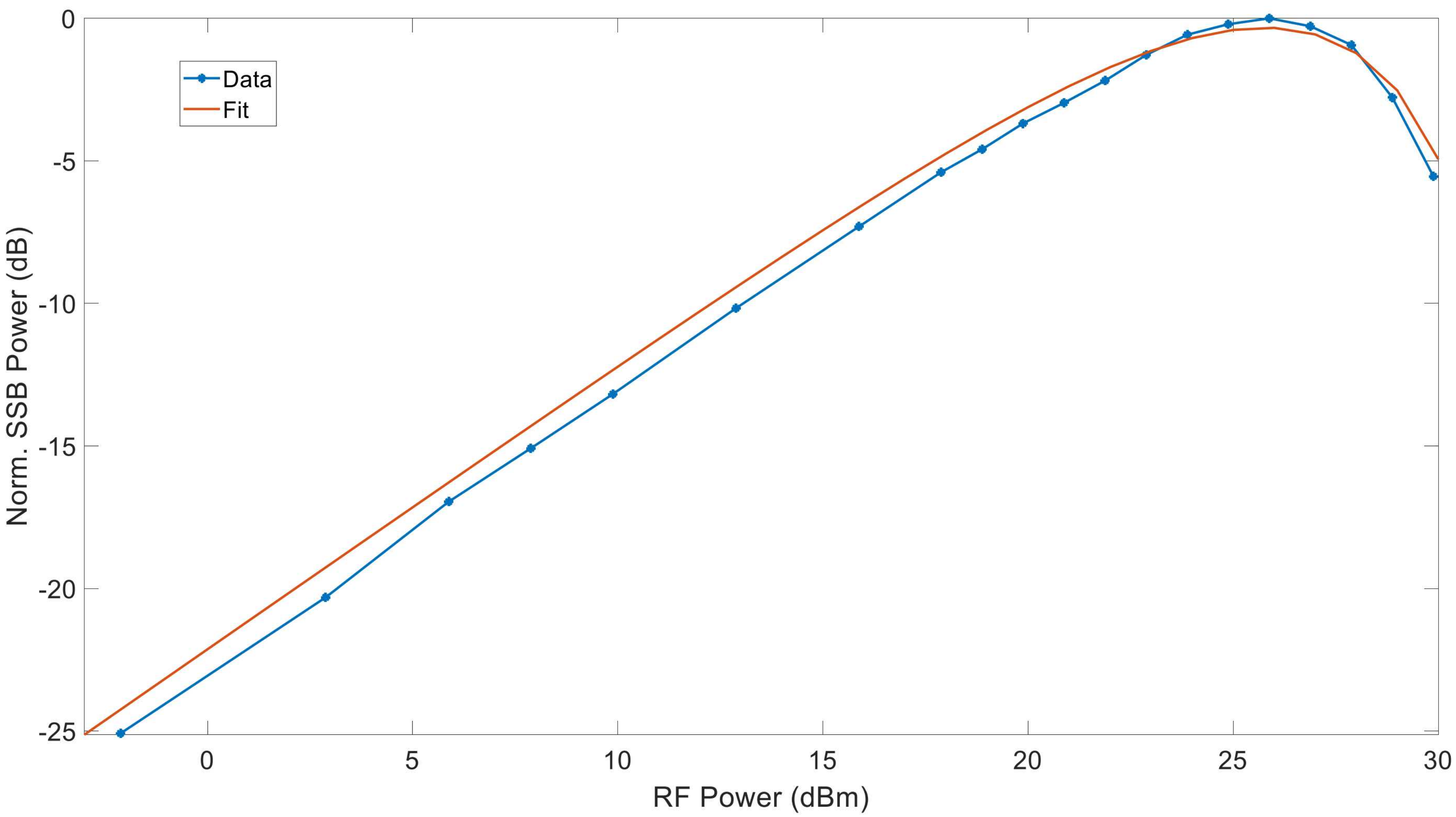


DC=-4 V



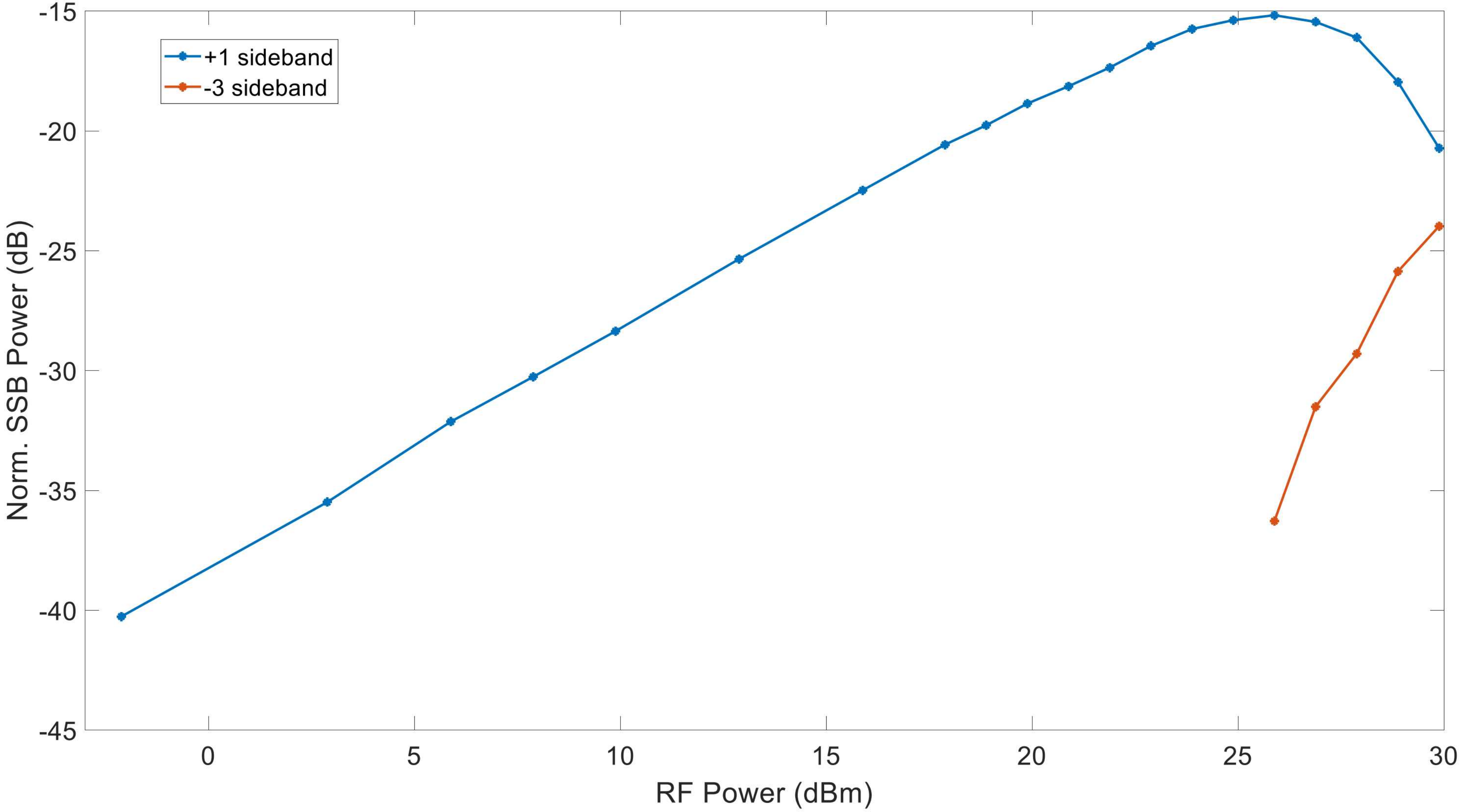
-1 & +3 sidebands cross-over for larger reverse bias

Bessel Fit



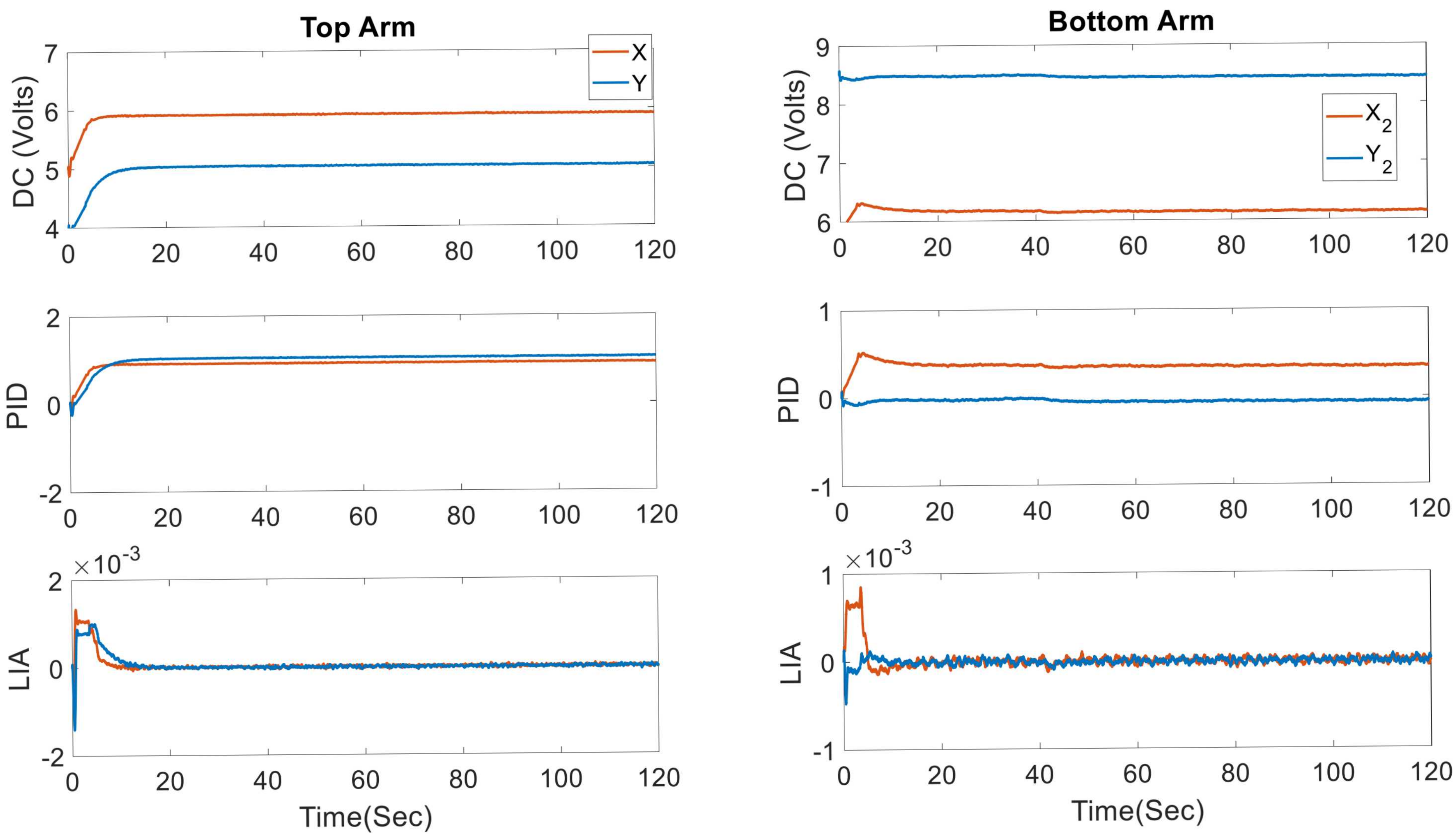
$V\pi$ = ~3.71 V (L=1mm);
$V\pi L$ = 0.371 V cm

Peak power

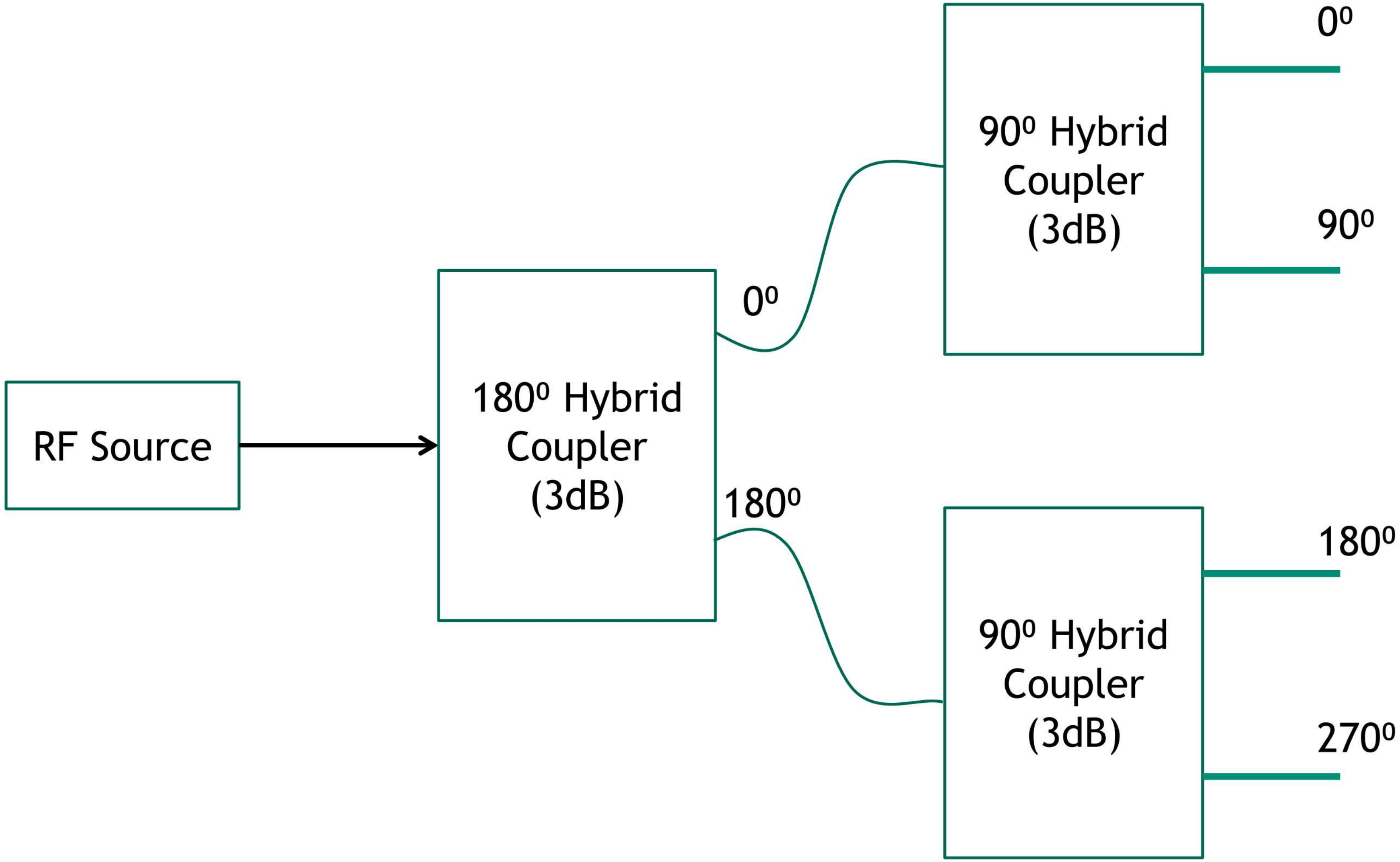


+1 sideband
-3 sideband
Norm. SSB Power (dB)
-15
-20
-25
-30
-35
-40
-45
0
5
10
15
20
25
30
RF Power (dBm)

Feedback



Top Arm
Bottom Arm
X
Y
X2
Y2
DC (Volts)
PID
LIA
×10-3
Time(Sec)
0
20
40
60
80
100
120


RF Source
180⁰ Hybrid Coupler (3dB)
0⁰
180⁰
90⁰ Hybrid Coupler (3dB)
0⁰
90⁰
90⁰ Hybrid Coupler (3dB)
180⁰
270⁰