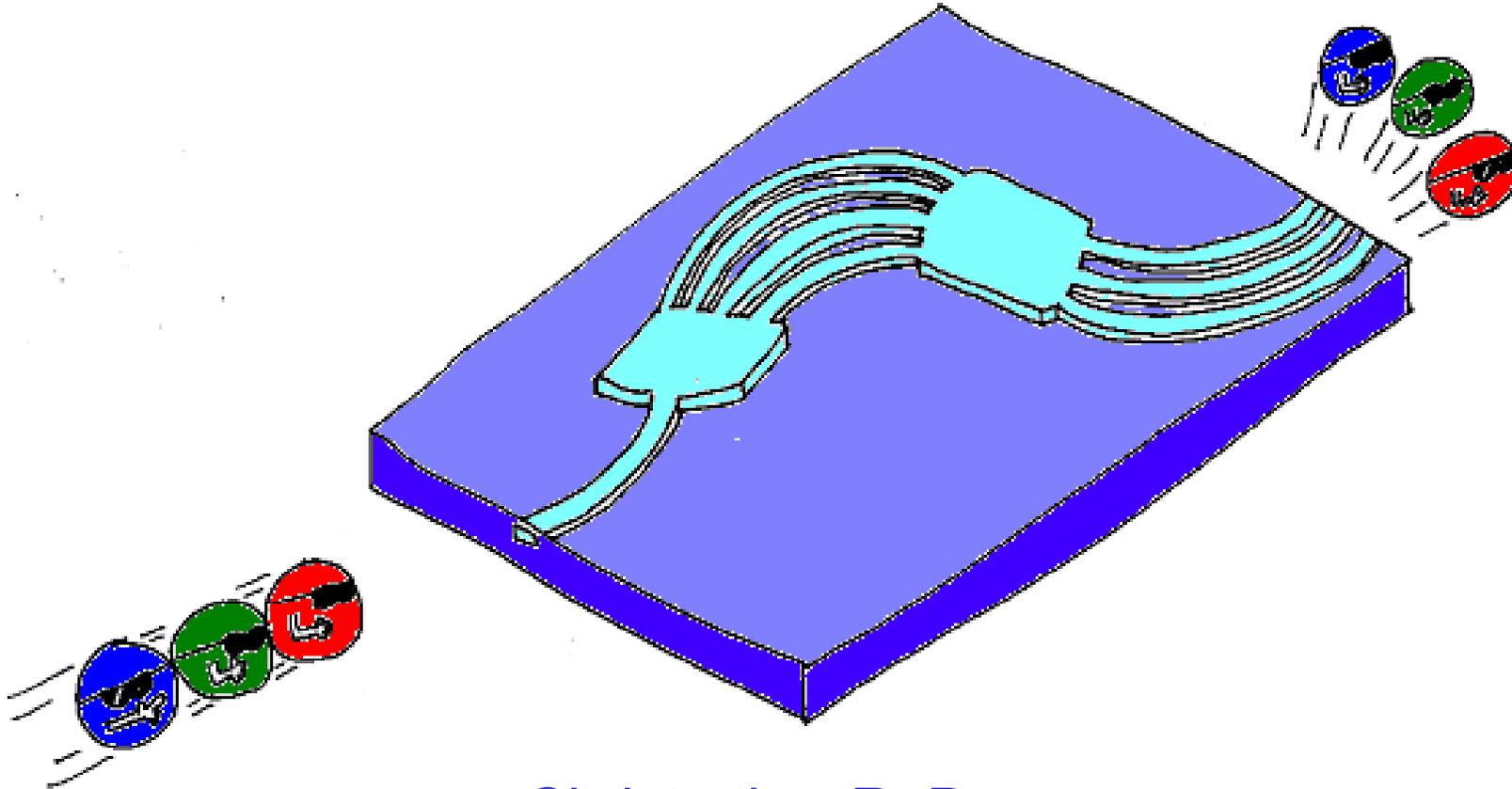


# Monolithic Devices for Advanced Modulation Formats



Christopher R. Doerr

# Outline

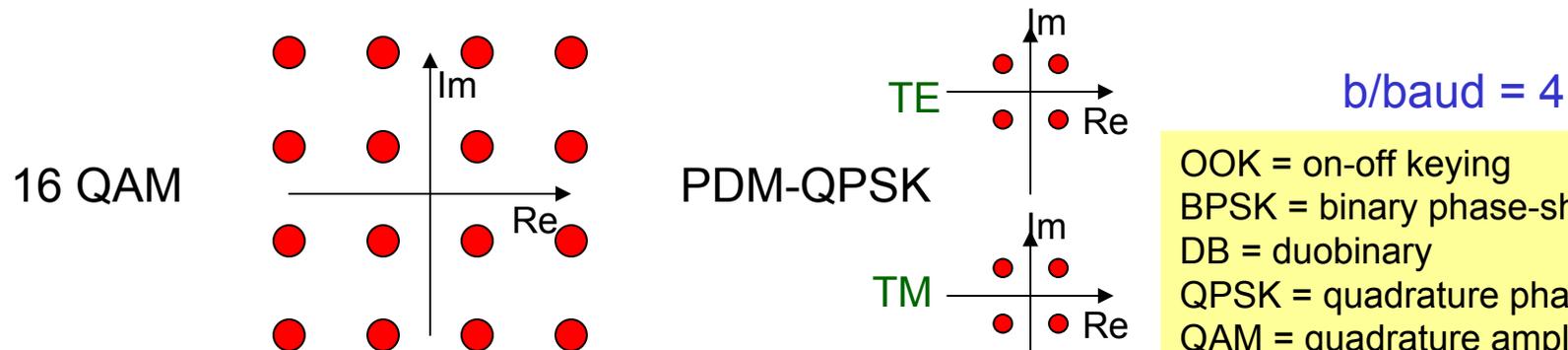
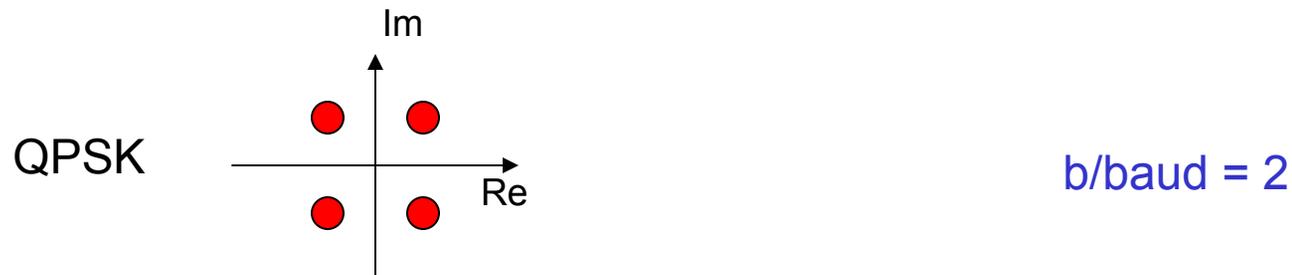
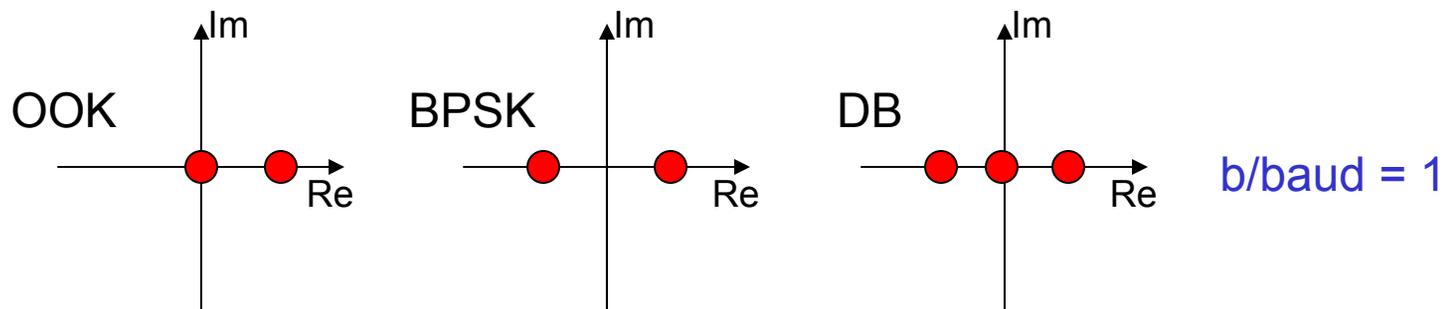
- Background
- Transmitters
- Receivers
- Predictions

(Note: limiting discussion to single-wavelength devices)

# Background

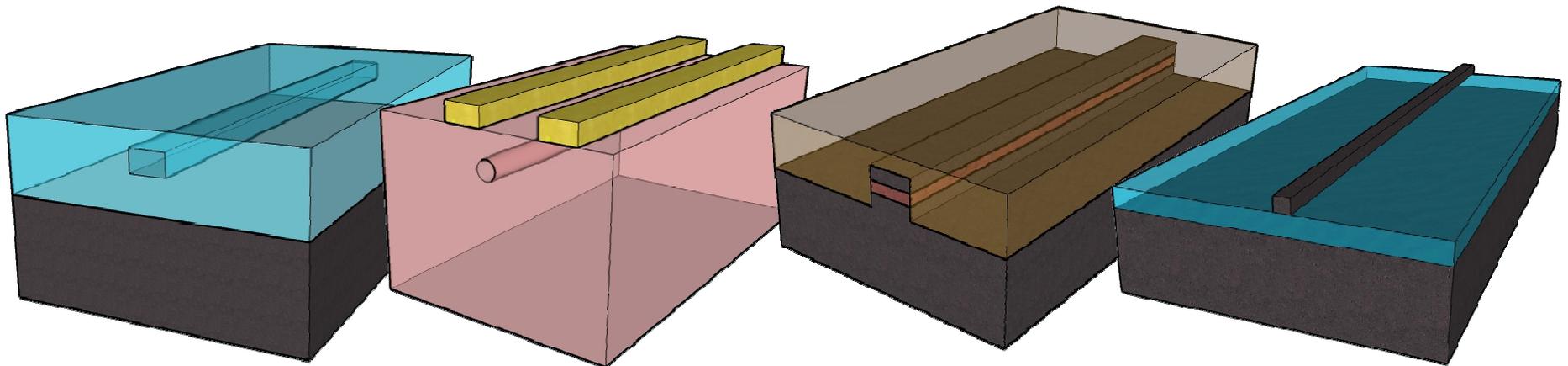
# Advanced modulation formats

Advanced modulation formats can increase the capacity of a single fiber and/or tolerance to filtering and dispersion



OOK = on-off keying  
BPSK = binary phase-shift keying  
DB = duobinary  
QPSK = quadrature phase-shift keying  
QAM = quadrature amplitude modulation  
PDM = polarization-division multiplexed

# Popular PIC material systems



Silica on silicon

Lithium niobate (LN)

Indium phosphide (InP)

Silicon on insulator (SOI)

Pro: Low loss, precise w.g.  
 Con: Mainly passive, large  
 Main product:: Mux/Demux

Pro: High speed, linear  
 Con: Large, expensive  
 Main product:: Modulator

Pro: Laser, high speed, compact  
 Con: Expensive, lossy  
 Main product:: Laser, receiver, modulator

Pro: High yield, compact  
 Con: No QCSE, no laser  
 Main product:: VOA, APD, receiver, modulator

# Hybrid vs. monolithic integration

- Hybrid / co-packaging
  - Separately optimized components
  - Increased yield
  - Easier for fab-less vendor
- Monolithic
  - Fewer packaging steps
  - Fewer testing steps
  - Fewer interconnections to manage
  - More net devices per fabrication run (usually)
  - Smaller footprint

# Transmitters

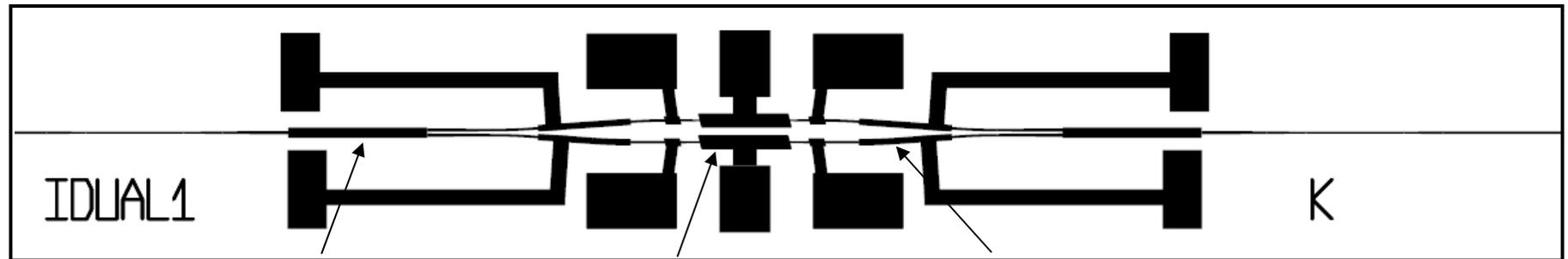
# Monolithic vs. hybrid integration for Tx

- Hybrid / co-packaging
  - Separately optimized components
  - Increased yield
  - Easier for fab-less vendor
- Monolithic
  - Fewer packaging steps
  - Fewer testing steps
  - Fewer interconnections to manage
  - More net devices per fabrication run (usually)
  - Smaller footprint

Best for laser + modulator in near term because single ch. adv. mod. Tx require tunable laser with high power and narrow linewidth

Best for modulator because requires many interconnections

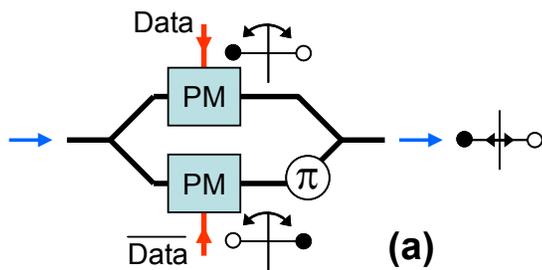
# 85-Gb/s duobinary modulator PIC



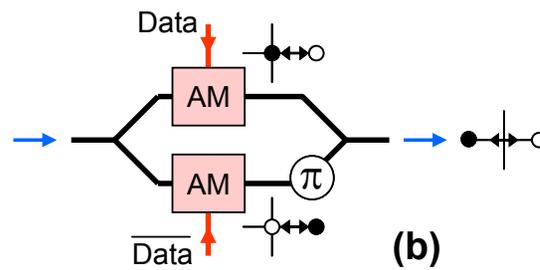
1 x2 MMI coupler

QCSE modulator

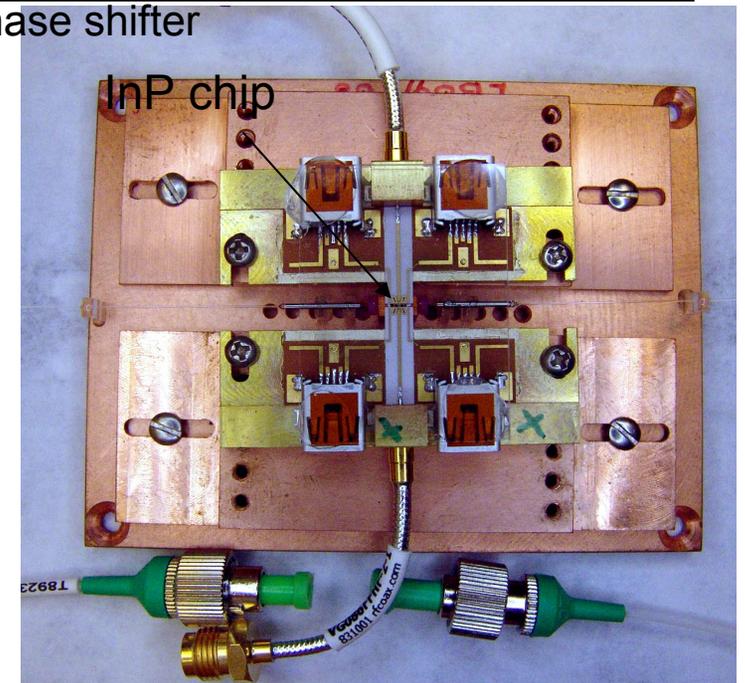
Phase shifter



(a)



(b)



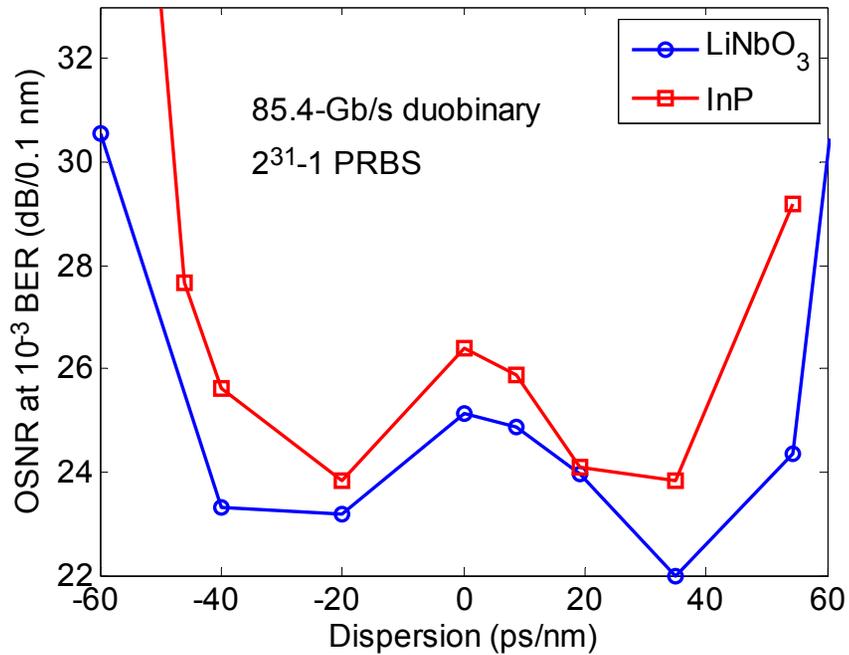
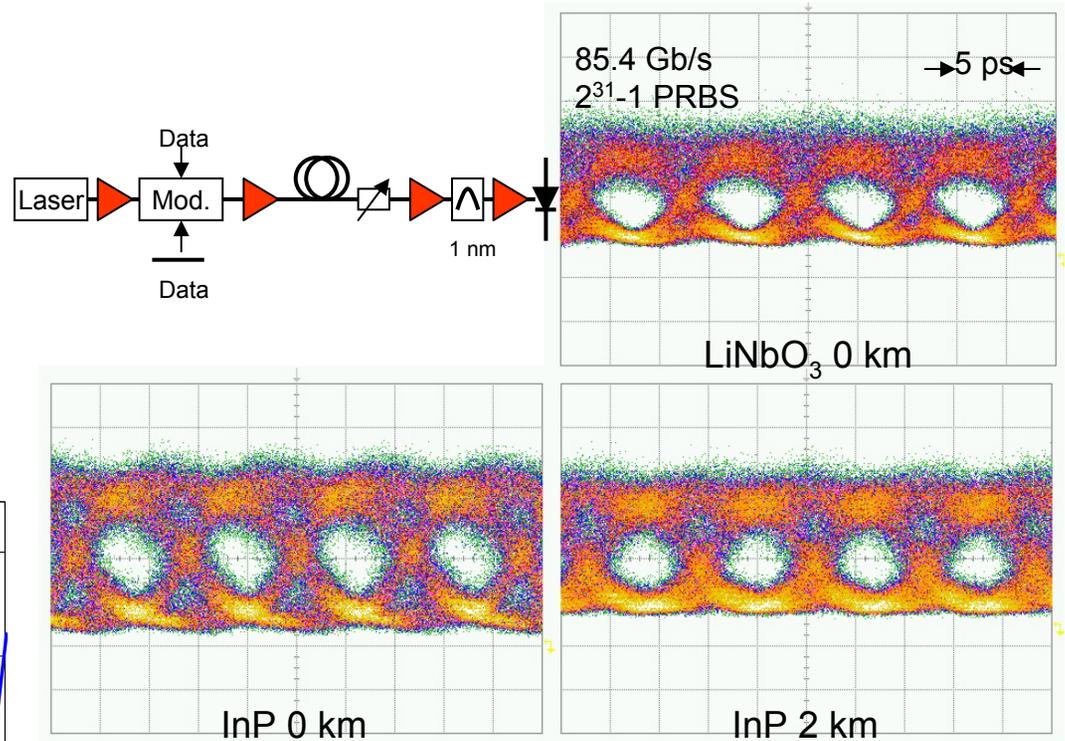
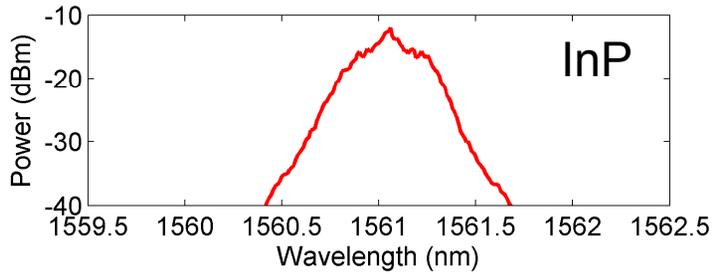
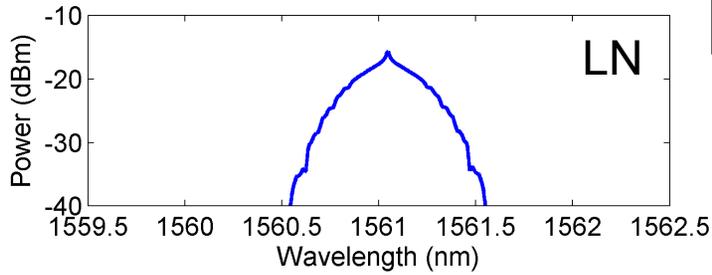
InP chip

C. R. Doerr, *IEEE Photon. Tech. Lett.*

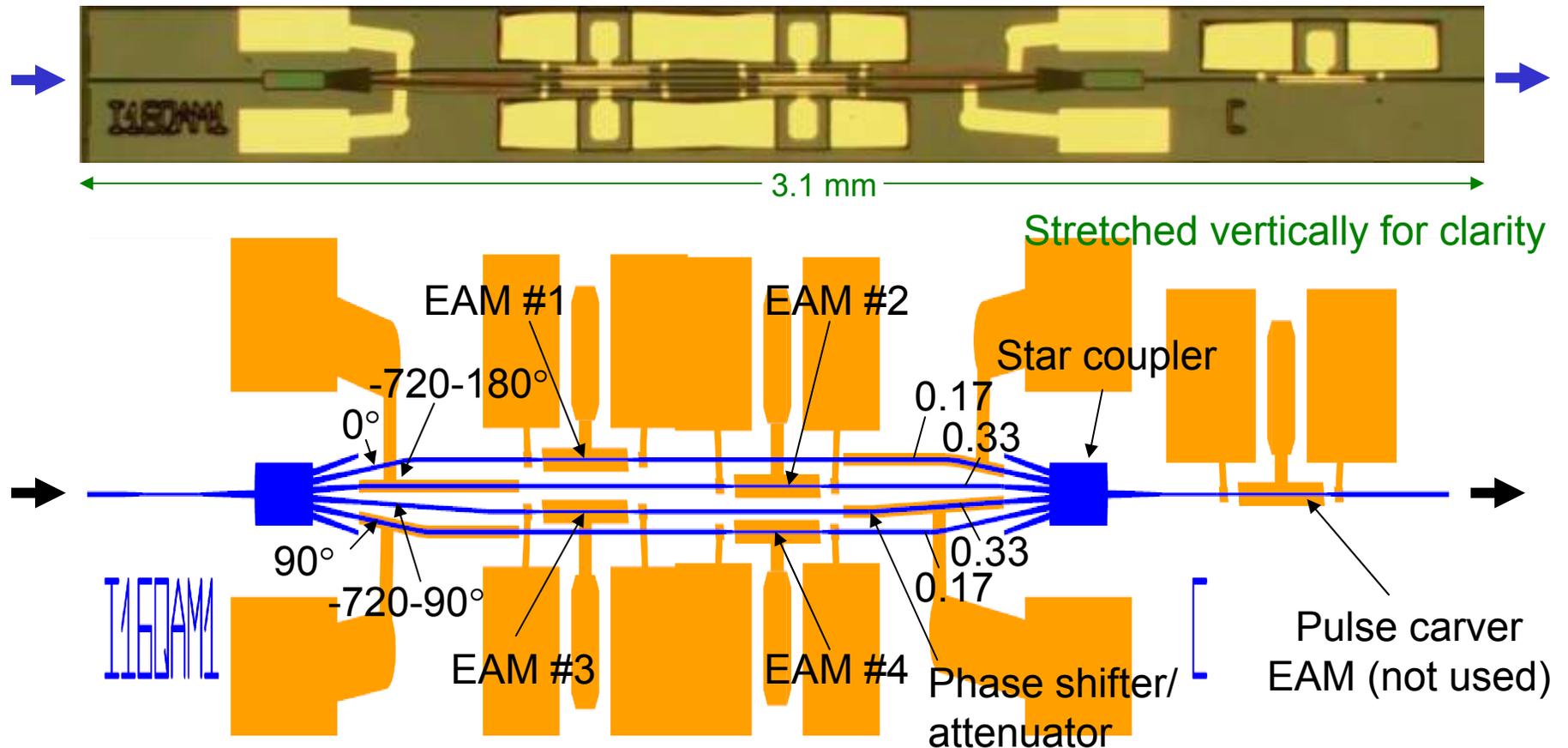
ECOC workshop, Sep. 2009, slide 9

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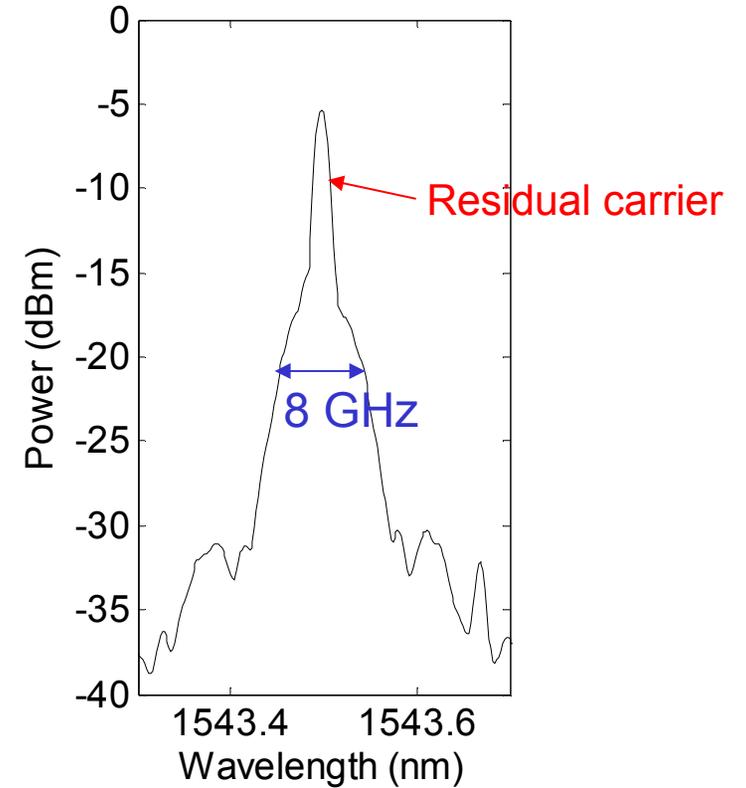
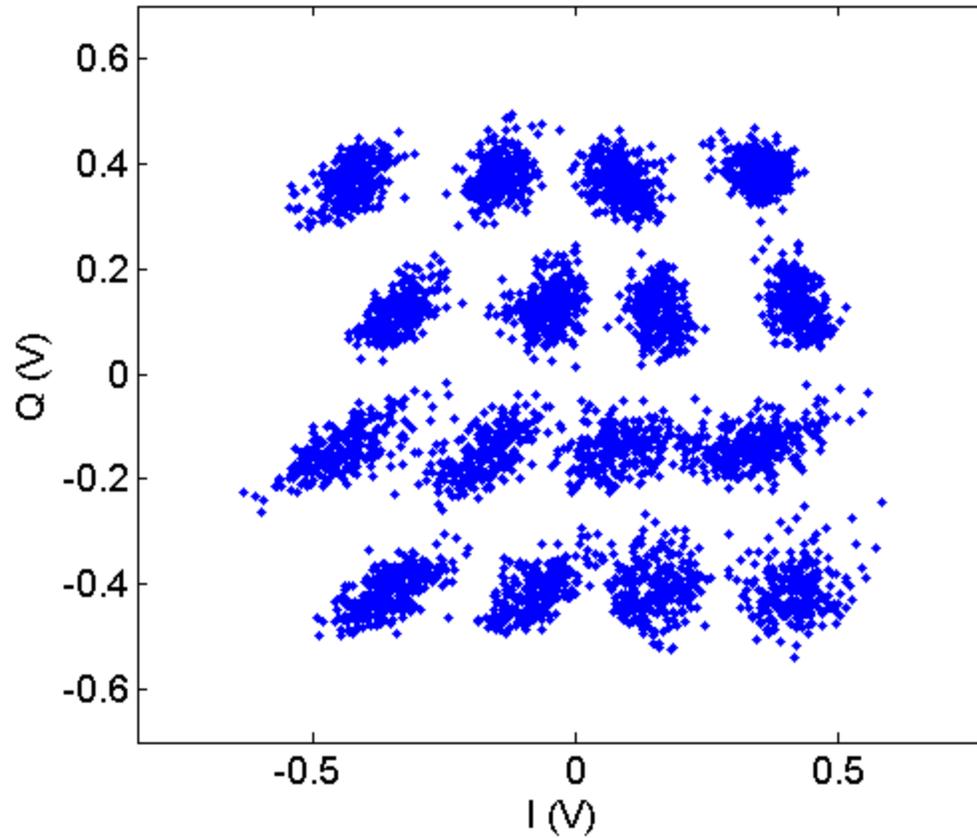
# Results



# 16 QAM modulator PIC



# Results



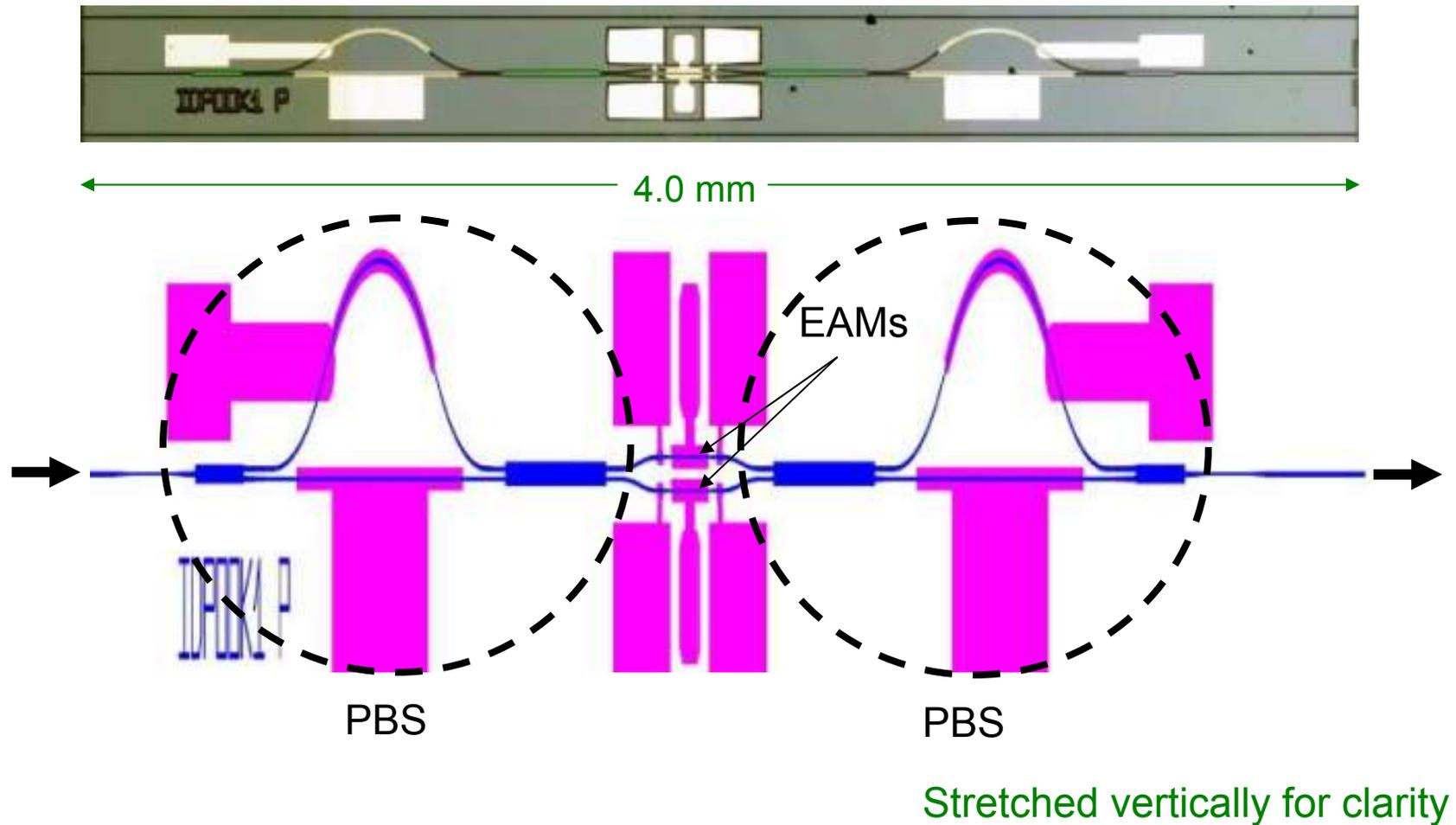
10.7 Gbaud  
 $2^{15}-1$  PRBS

BER for Q quadrature =  $9.3 \times 10^{-4}$   
BER for I quadrature = high due to shifting

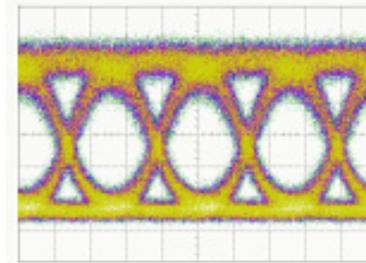
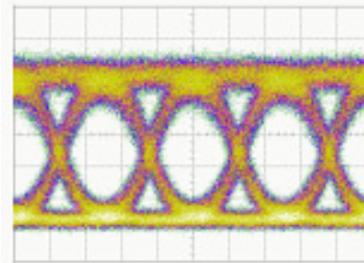
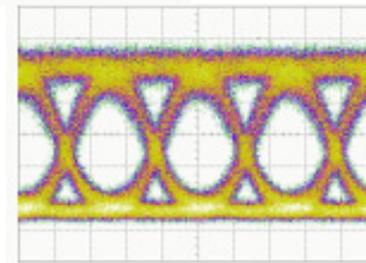
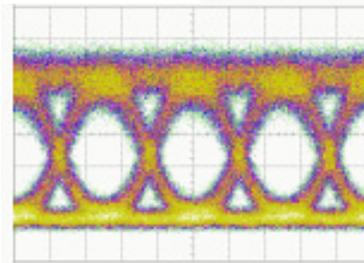
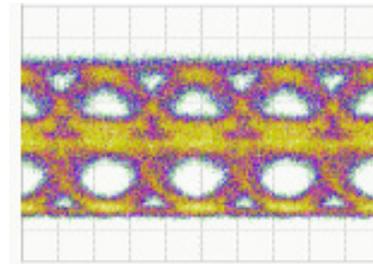
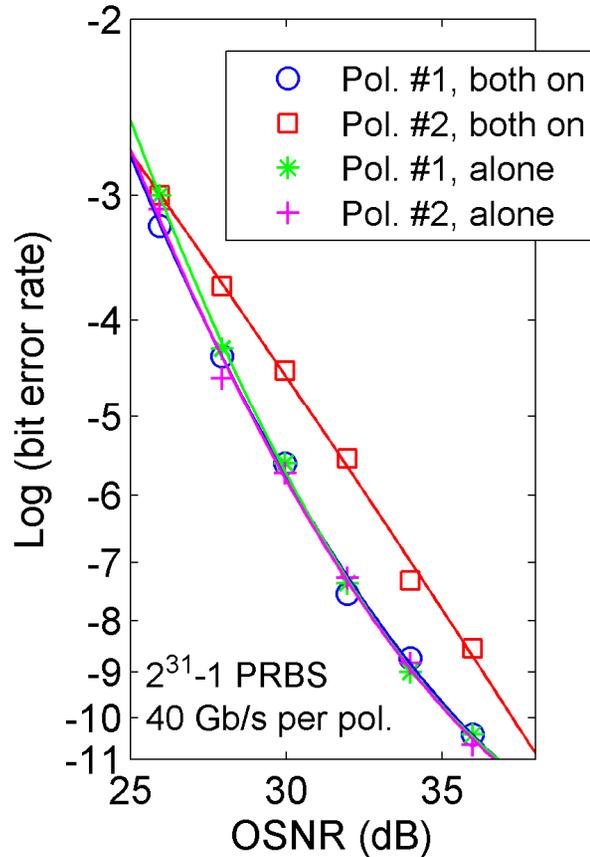
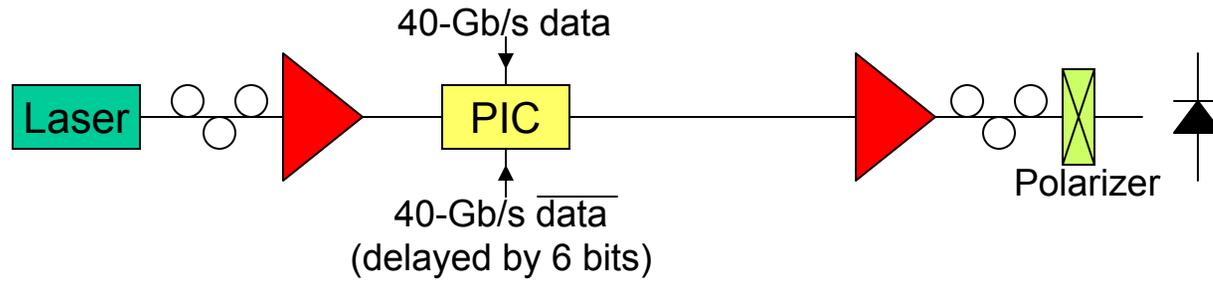
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# PDM-OOK modulator PIC



# Results



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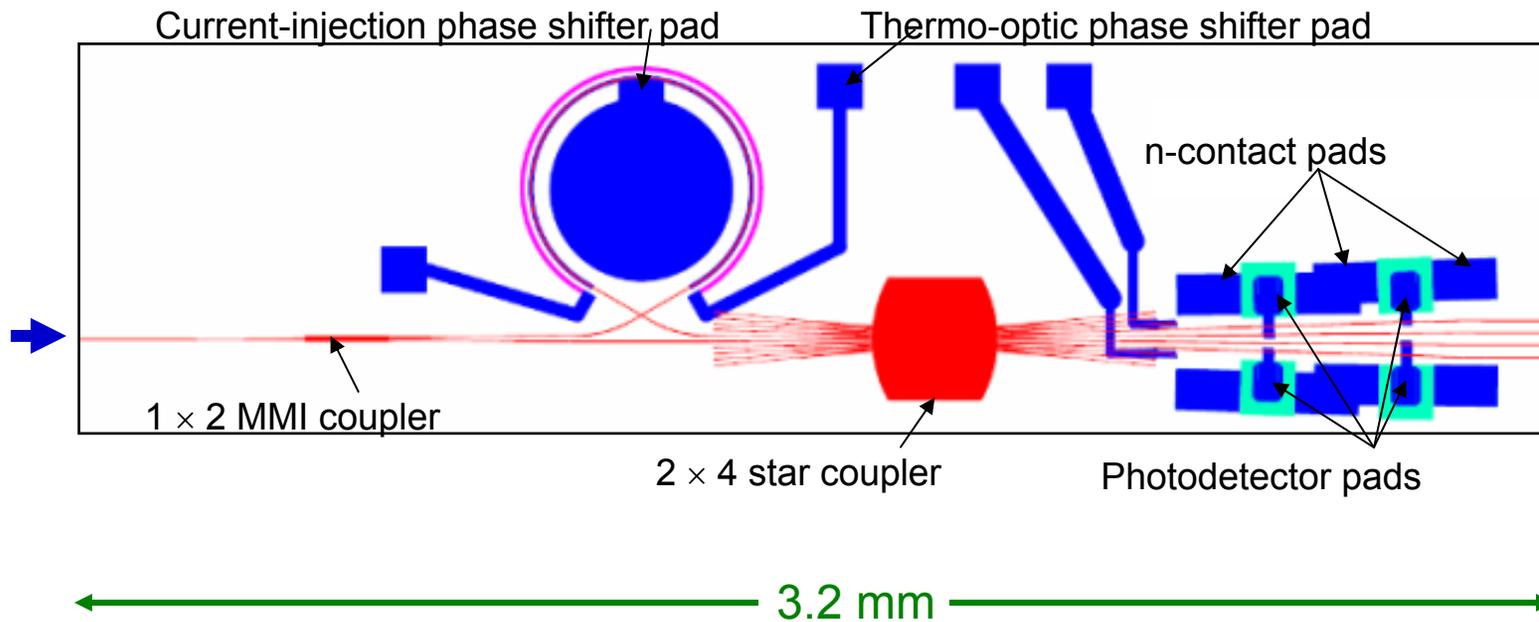
# Receivers

# Monolithic vs. hybrid integration for Rx

- Hybrid / co-packaging
  - Separately optimized components
  - Increased yield
  - Easier for fab-less vendor
- Monolithic
  - Fewer packaging steps
  - Fewer testing steps
  - Fewer interconnections to manage
  - More net devices per fabrication run (usually)
  - Smaller footprint

Best for Rx because Rx requires no active components and many interconnections. Main drawback is insertion loss.

# DQPSK receiver PIC

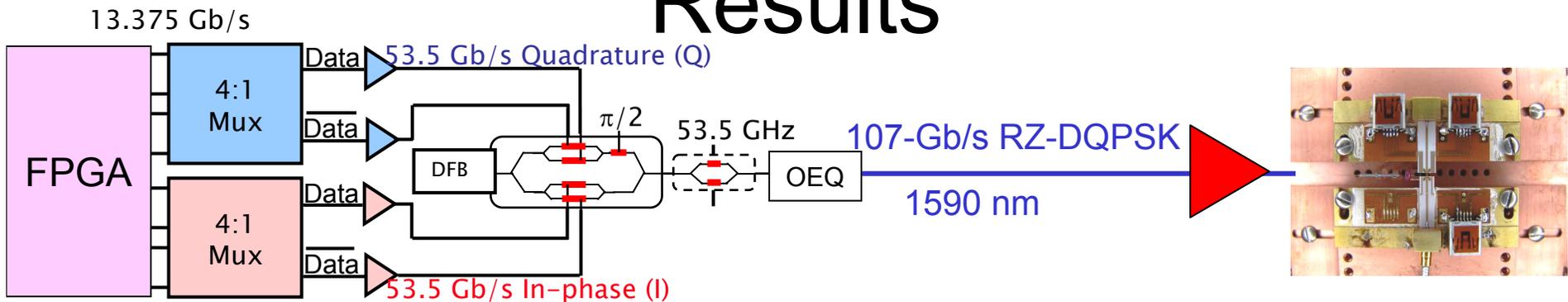


C. R. Doerr, et al., OFC, PDP23, 2008.

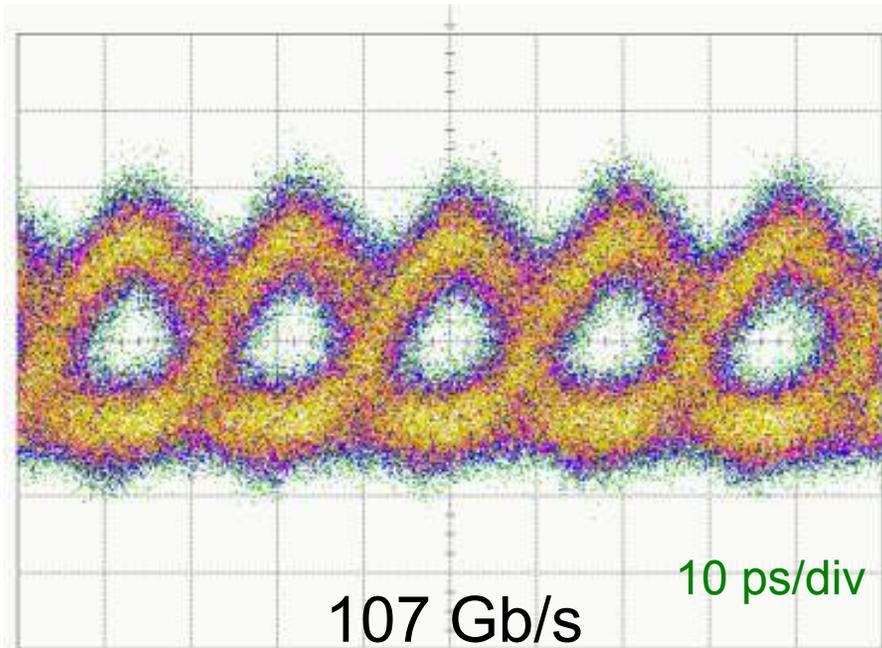
ECOC workshop, Sep. 2009, slide 17

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# Results



Courtesy of P. J. Winzer



(single-ended detection)

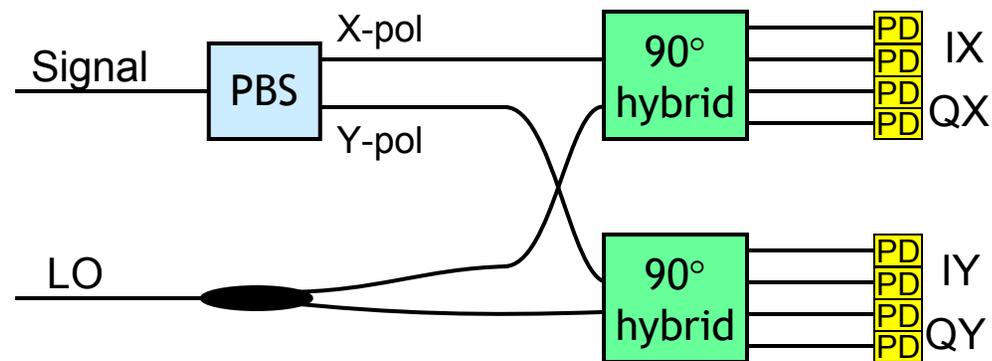
Pre-coded, FEC encoded SONET pattern with  $2^{31}-1$  PRBS payload

Error floor at  $6 \times 10^{-4}$  BER

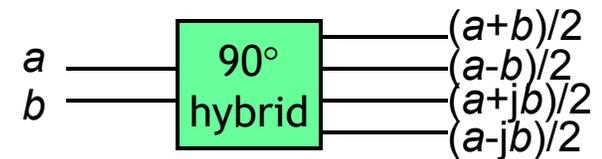
The FEC corrected it to error free



# Conventional coherent receiver



- 12 intra-component connections
- Skew must be kept small

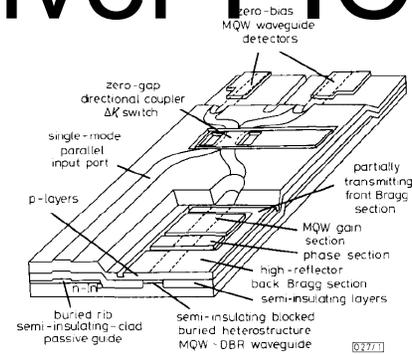


# Coherent receiver PICs

## Single pol., single quad. coherent Rx PIC

*T. L. Koch, et al., Electron. Lett., vol. 25, pp. 1621-1622, 1989.*

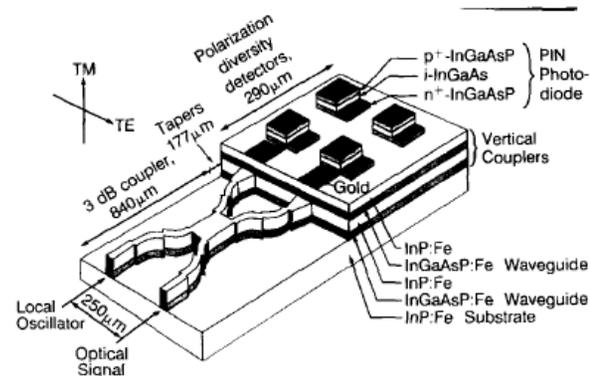
*Also, H. Takeuchi, et al., IEEE Photon. Tech. Lett., vol. 1, pp. 398-400, 1989.*



III-V

## Dual pol., single quad. coherent Rx PIC

*R. J. Deri, et al., IEEE Photon. Tech. Lett., p. 1238, 1992.*



III-V

## Single pol., dual quad. coherent Rx PIC

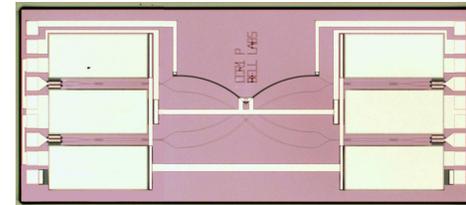
*H.-G. Bach, et al., OFC, OMK5, 2009.*



III-V

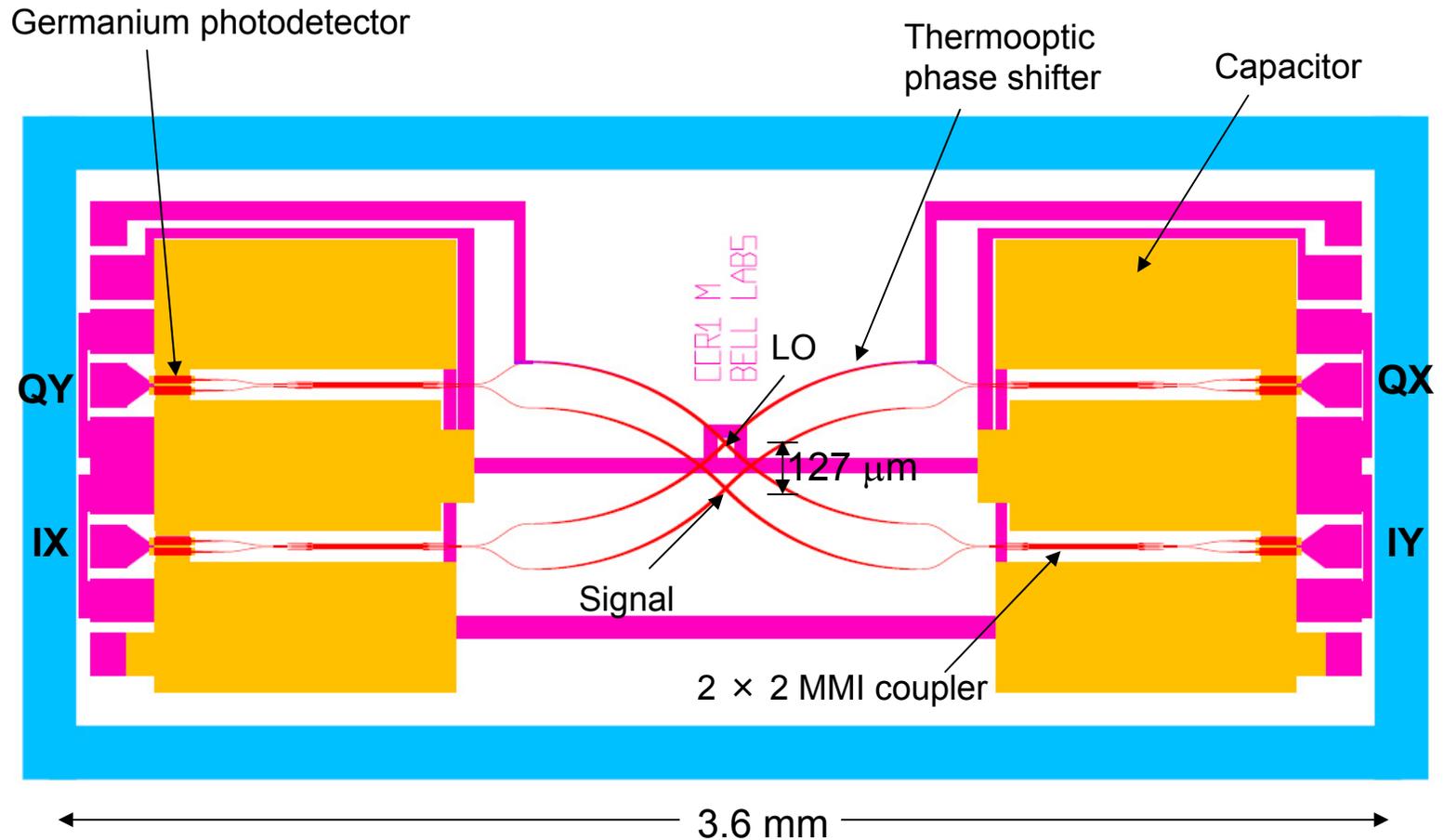
## Dual pol., dual quad. coherent Rx PIC

*C. R. Doerr, et al., OFC, PDPB2, 2009.*

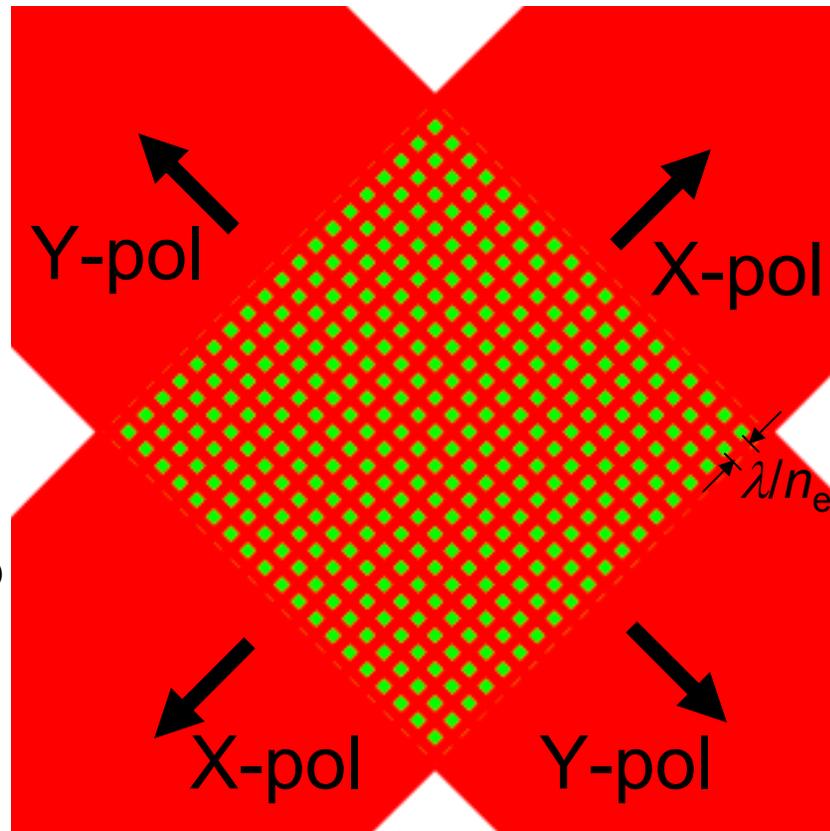
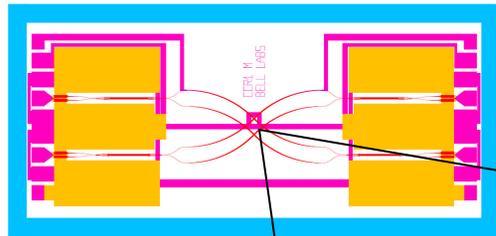


IV

# Si/Ge dual pol. dual quad. coherent Rx PIC



# Grating coupler



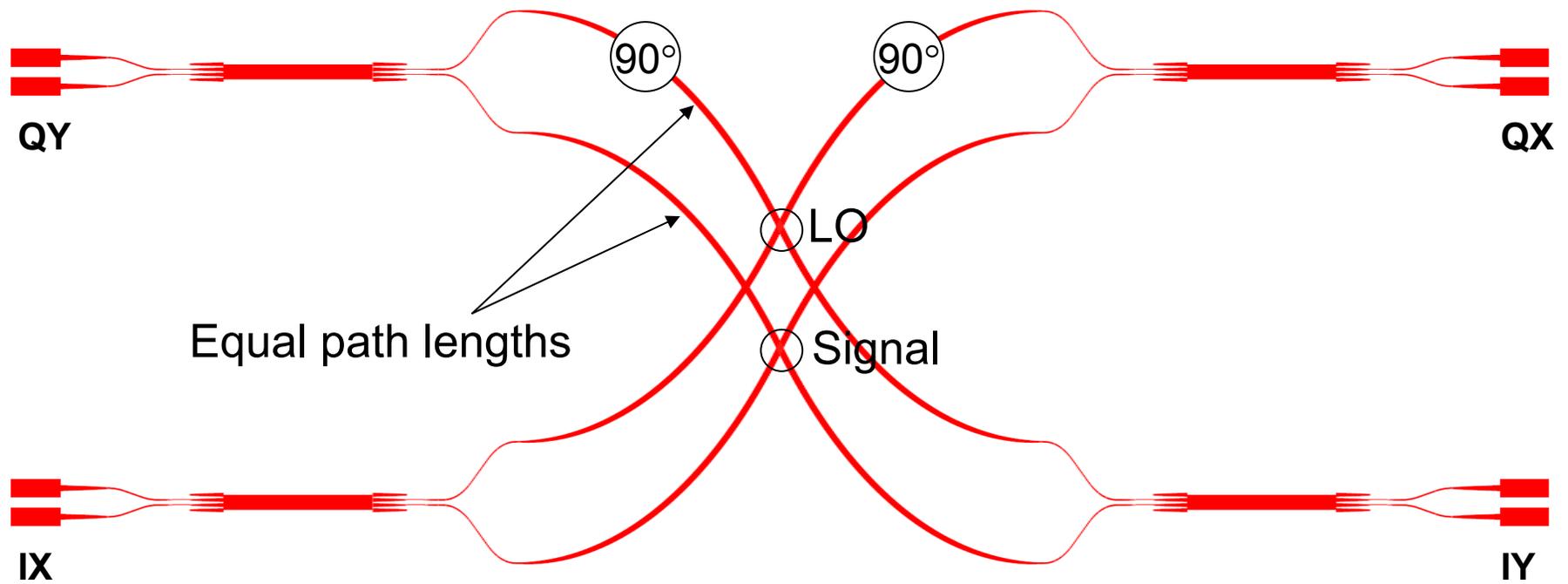
- Grating coupler serves as
1. fiber coupler
  2. spot-size converter
  3. polarization splitter
  4. two 50/50 splitters

D. Taillert, et al., *IEEE Photon. Technol. Lett.*, pp. 1249, 2003.

ECOC workshop, Sep. 2009, slide 22

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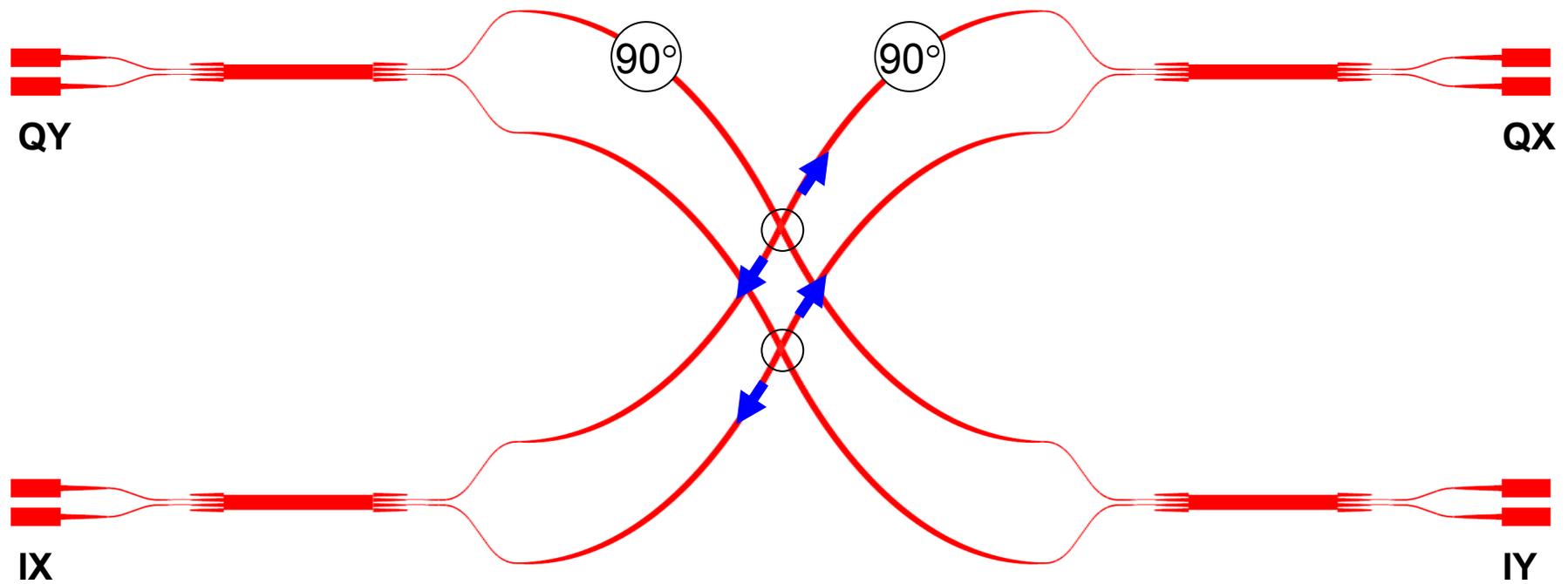
# Principle of operation



Stretched vertically for clarity

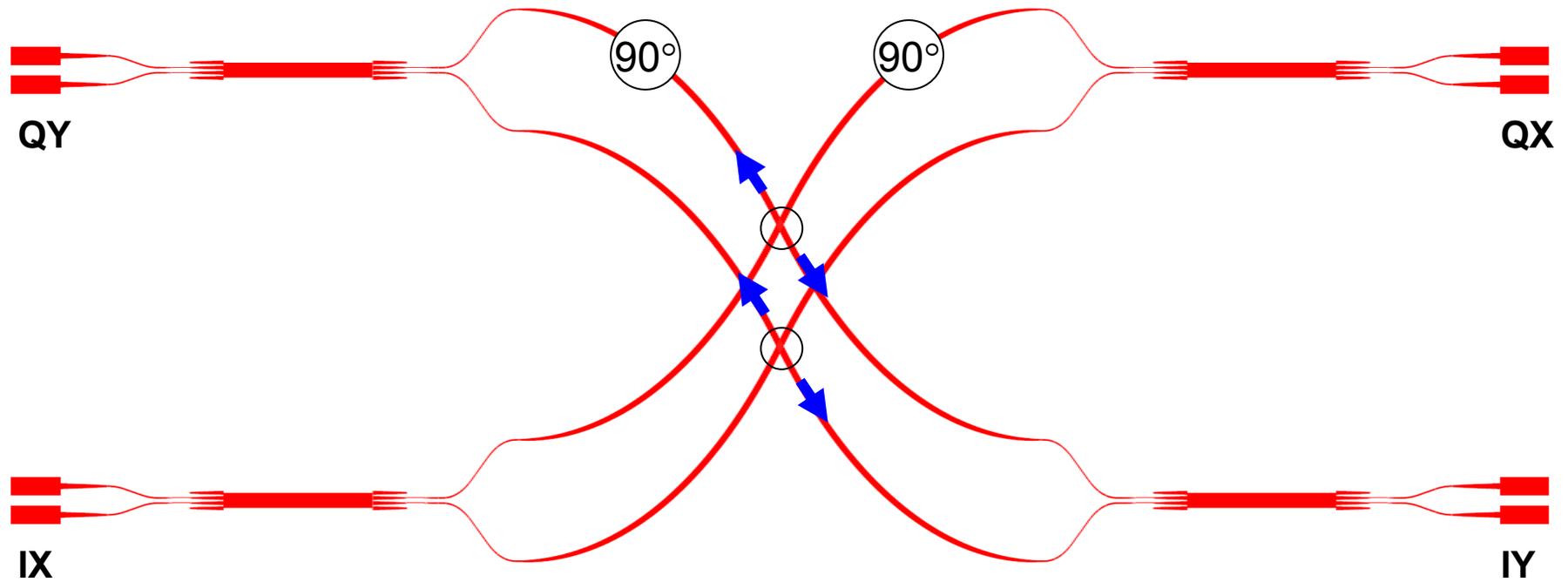
# Principle of operation

## X polarization

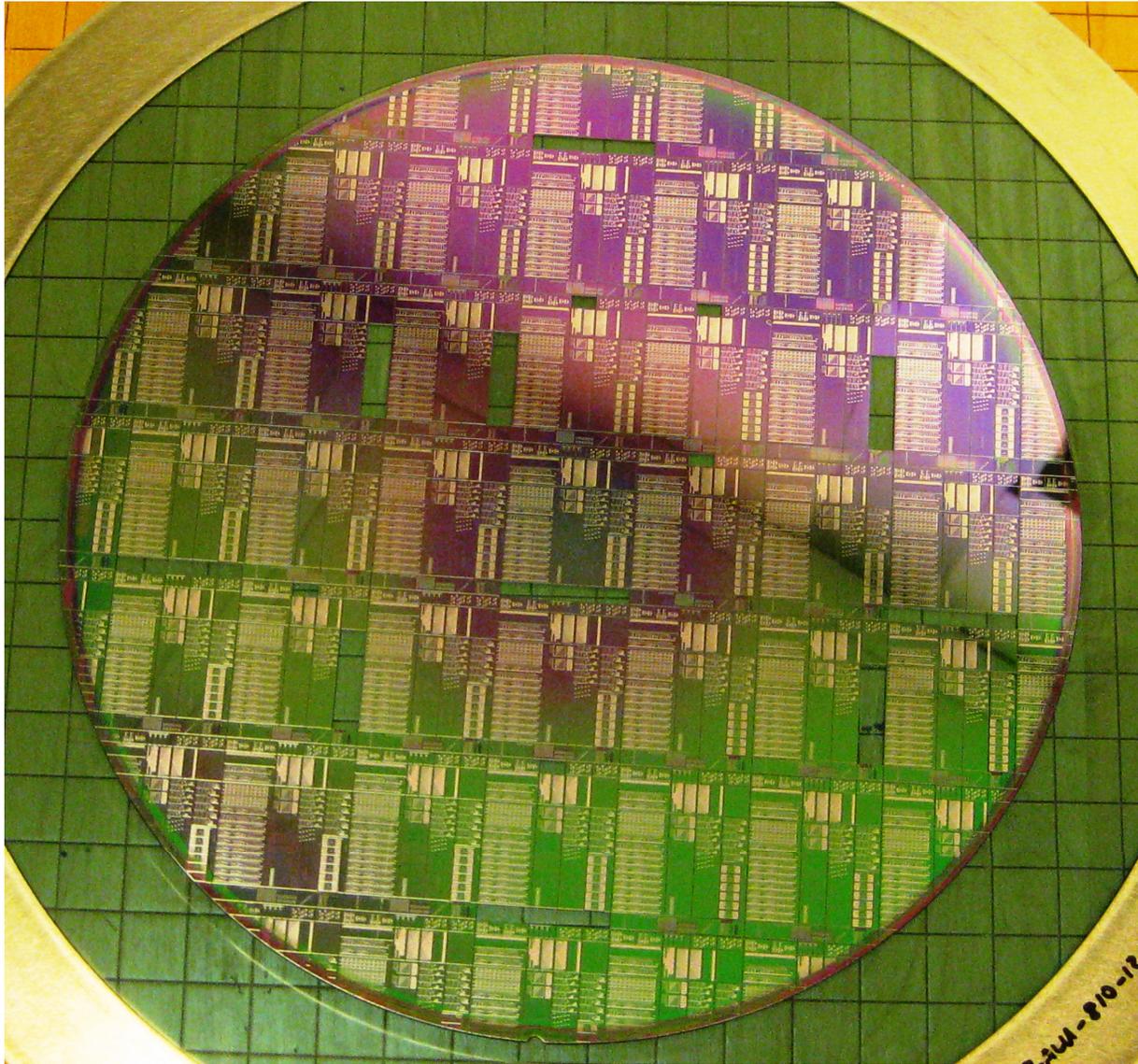


# Principle of operation

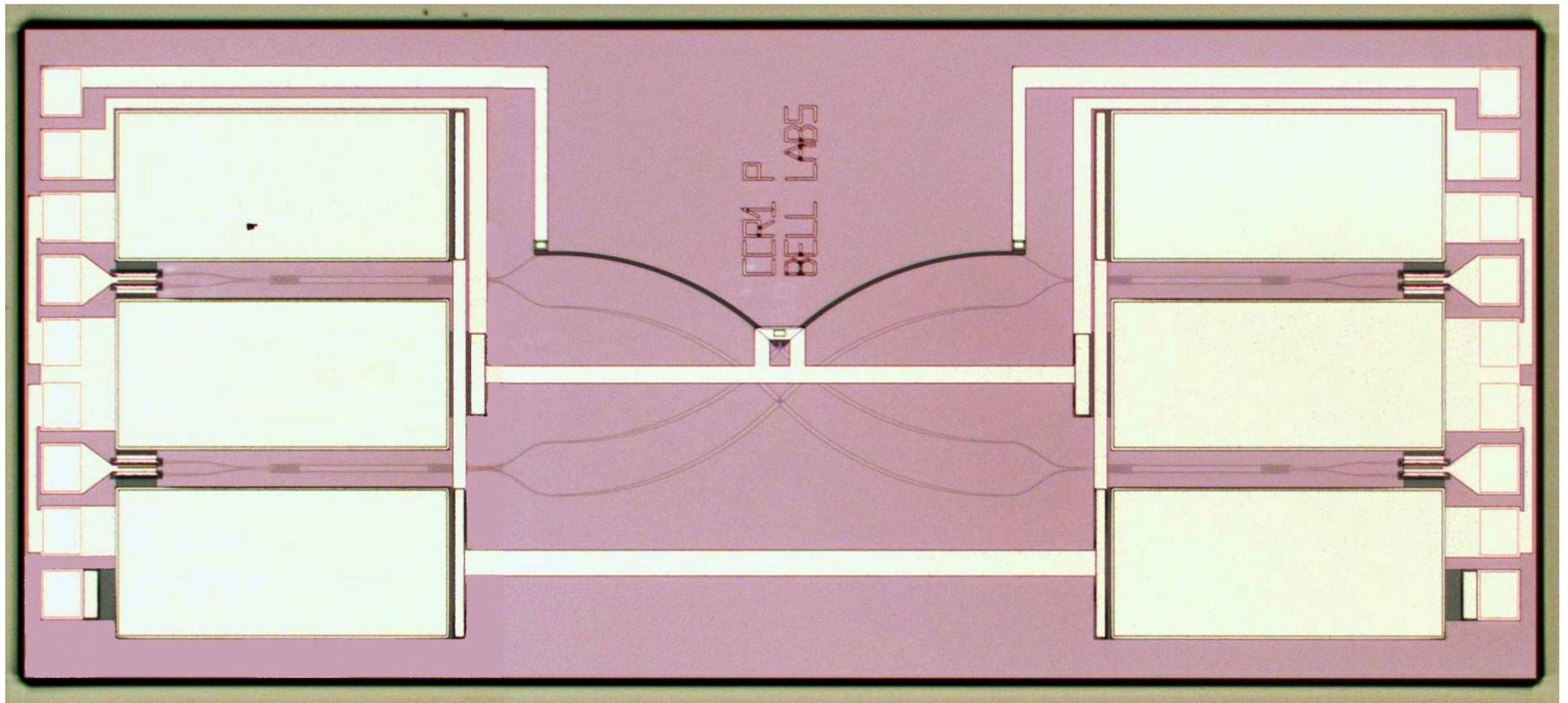
## Y polarization



# 8" wafer

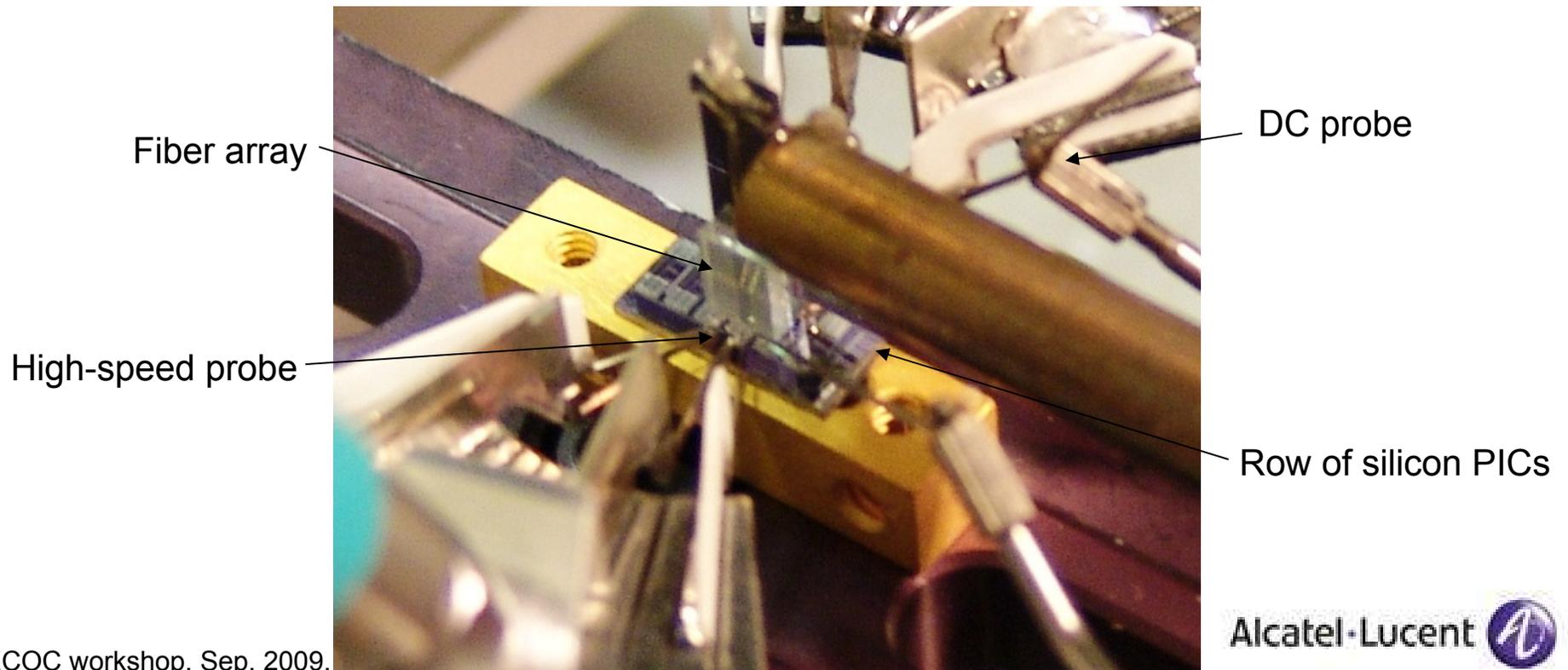
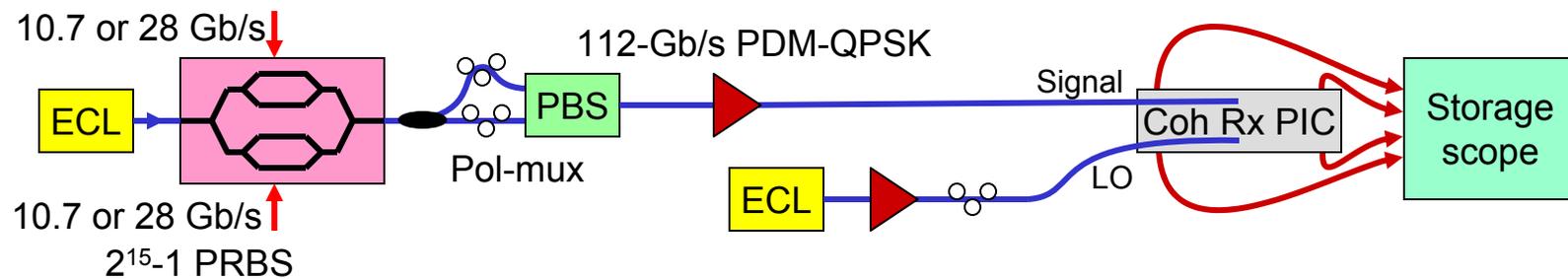


# Photograph of PIC

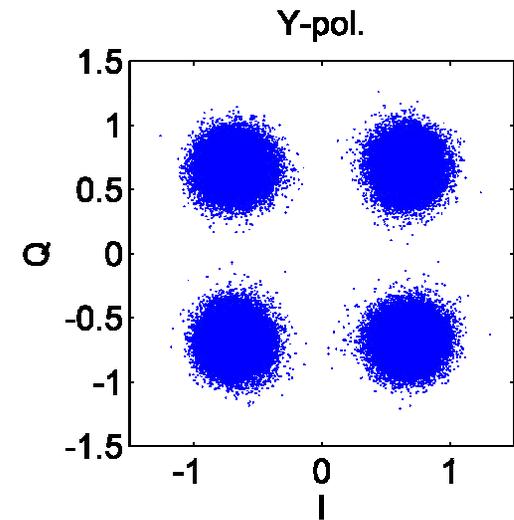
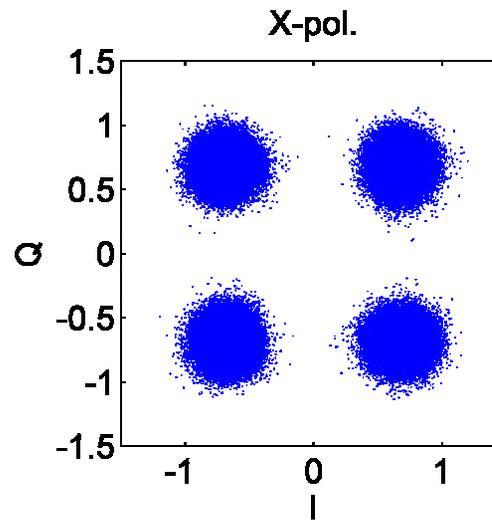
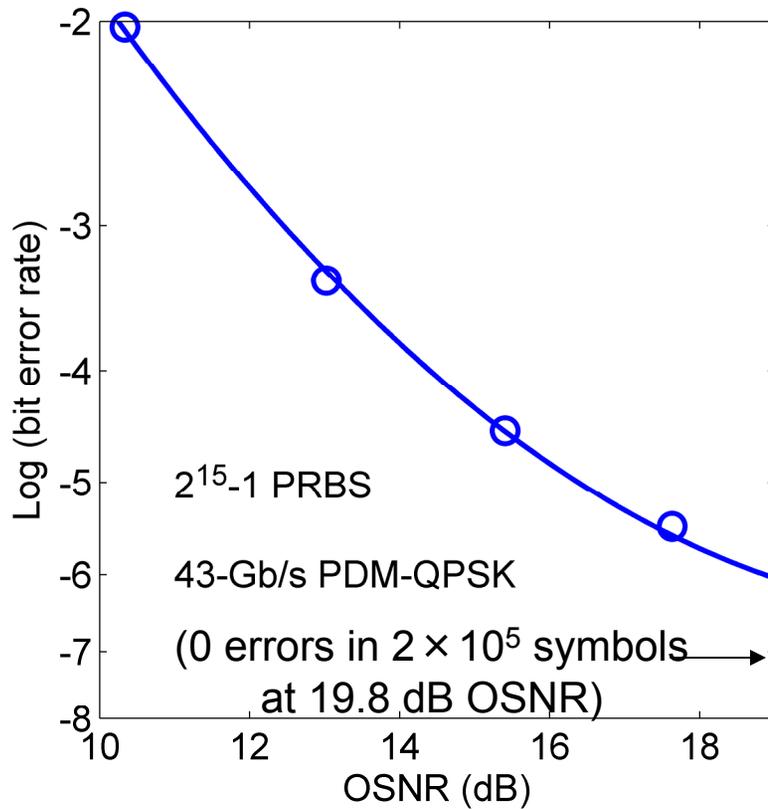


← 3.6 mm →

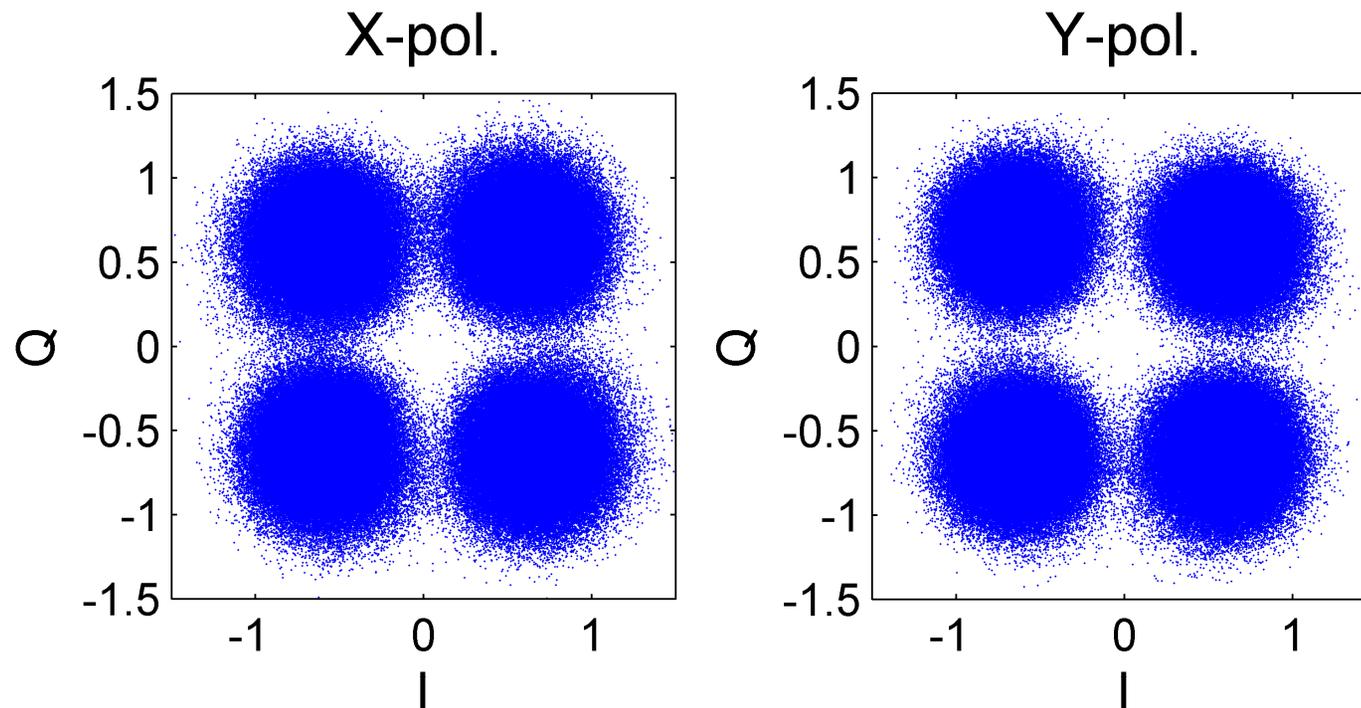
# Experimental setup



# 43-Gb/s results



# 112-Gb/s results



112-Gb/s  
2<sup>15</sup>-1 PRBS

$$\text{BER} = 1.7 \times 10^{-3}$$

Mainly limited by PD bandwidth of ~5 GHz (receiving 28 Gbaud)

# My predictions

- 5 years from now
  - **Hybrid** adv. mod. transmitters prevalent
    - Technology: InP + LiNbO<sub>3</sub> and InP + InP
  - **Hybrid** differential and coherent receivers prevalent
    - Technology: silica PLC + InP
- 10 years from now
  - **Monolithic** adv. mod. PICs (16-QAM, etc) prevalent
    - Technology: InP
  - **Monolithic** differential and coherent receiver EPICs prevalent
    - Technology: Silicon
  - Transmitter **EPICs** emerging
    - Technology: InP or silicon

# Additional predictions

- 5 years from now
  - Adv. mod. formats spread from long-haul to metro
  - Concerns on power consumption of coherent reception arise
- 10 years from now
  - Long haul using extremely adv. mod. formats
    - 256 QAM?
  - Adv. mod. formats spread to short reach
  - Low-power-consumption adv. mod. detection is paramount
    - Return to optical dispersion compensation
    - Return to differential detection

Special thank you to L. Zhang, L. Buhl, P. Winzer, P. Bernasconi, N. Sauer, J. Sinsky, A. Adamiecki, A. H. Gnauck, G. Raybon, L. Chen, N. Weimann, D. Neilson, Y.K. Chen, M. Zirngibl