The enabling role of graphene in integrated optics

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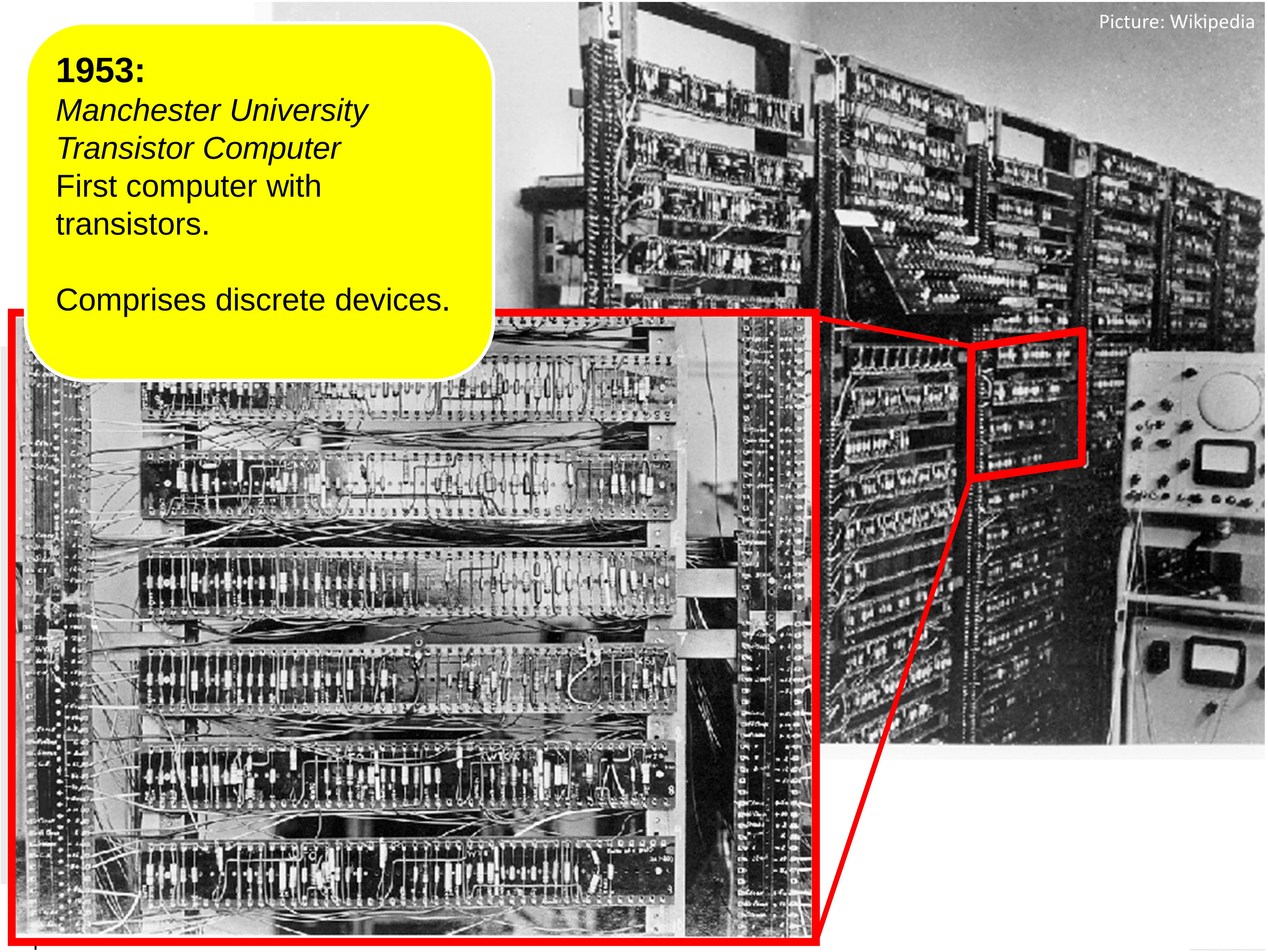
1953:
Manchester University Transistor Computer
First computer with transistors.

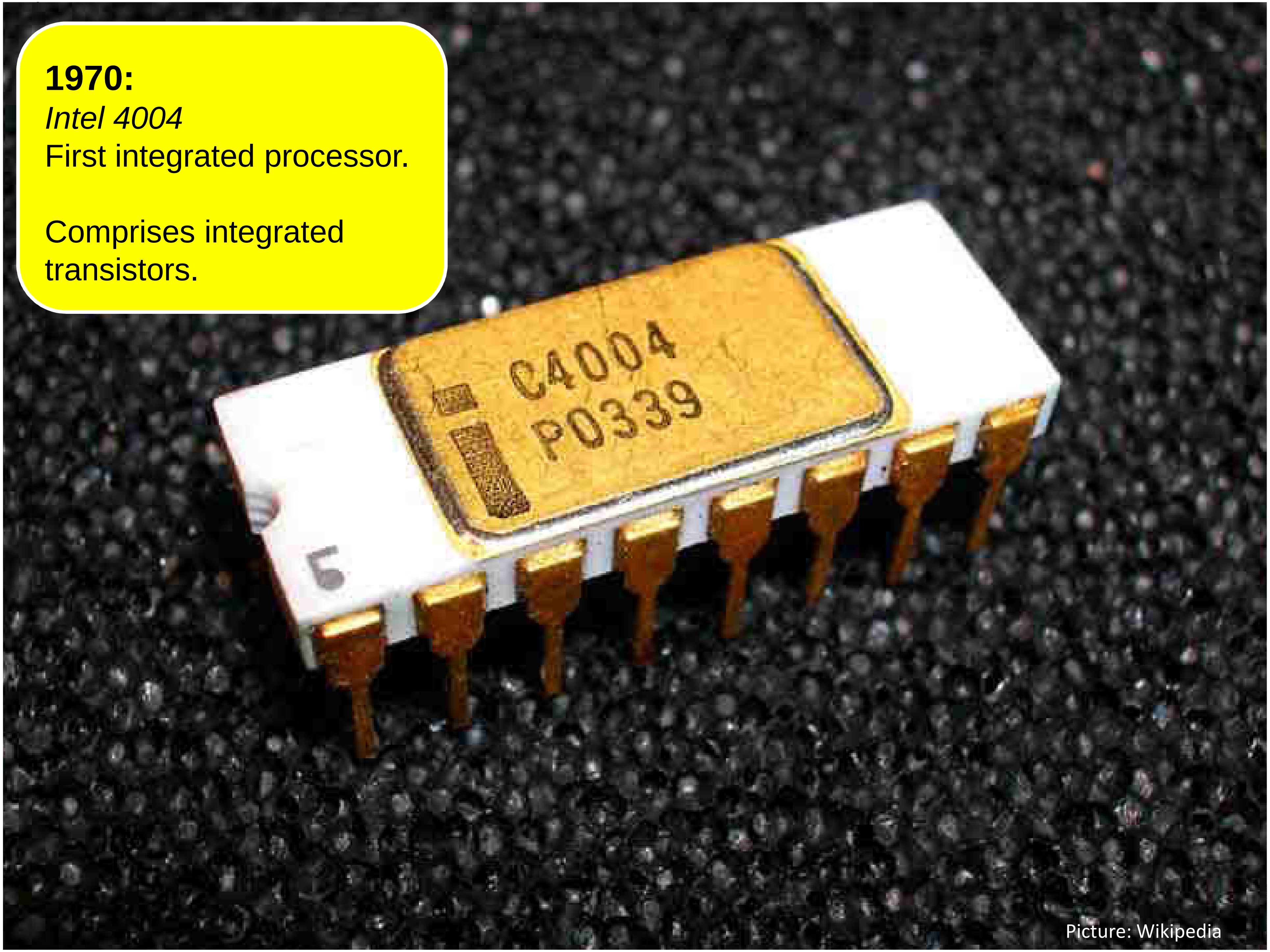
Comprises discrete devices.



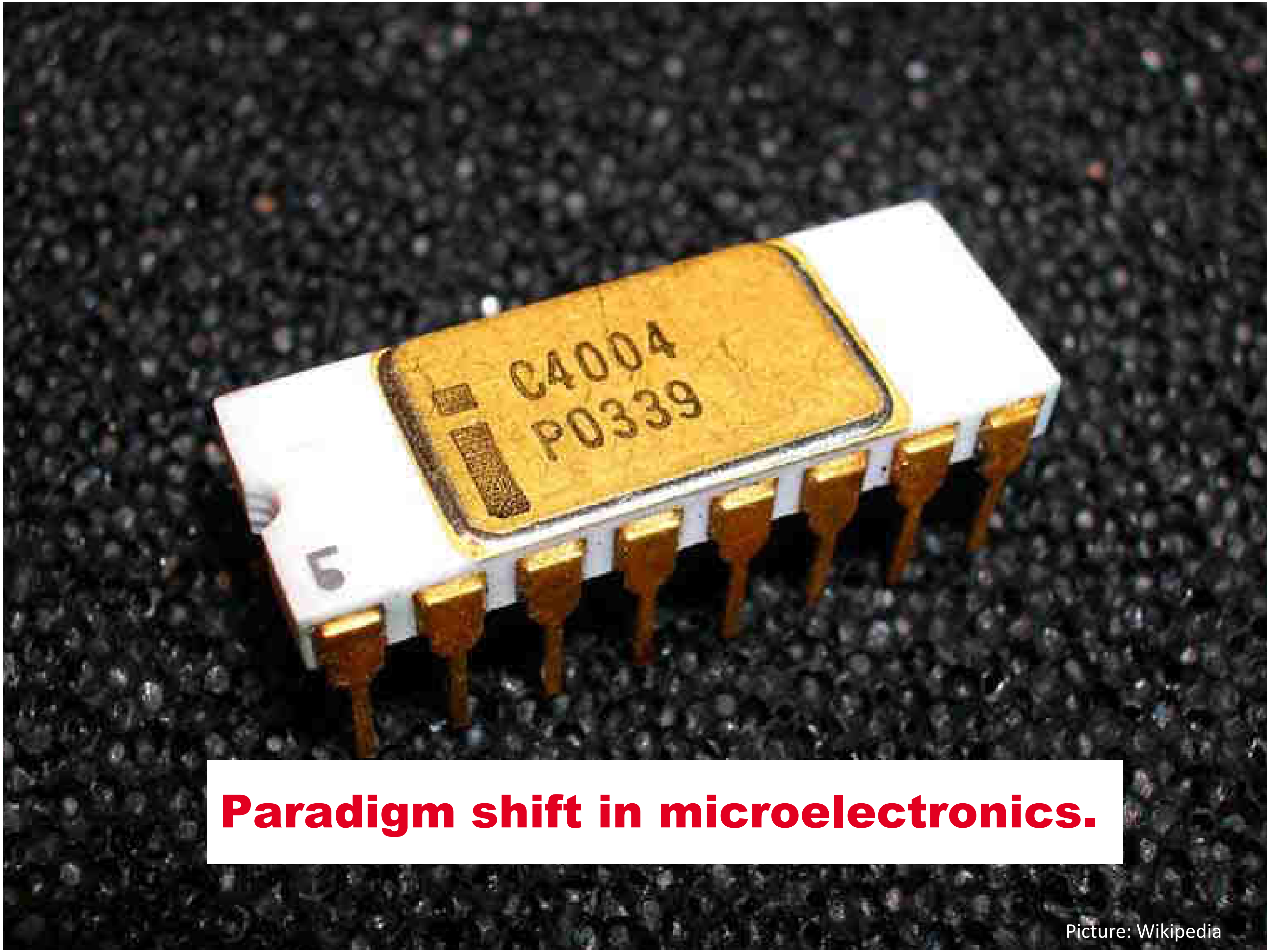
Picture: Wikipedia

1970:
Intel 4004
First integrated processor.

Comprises integrated transistors.



Picture: Wikipedia



Paradigm shift in microelectronics.

Picture: Wikipedia

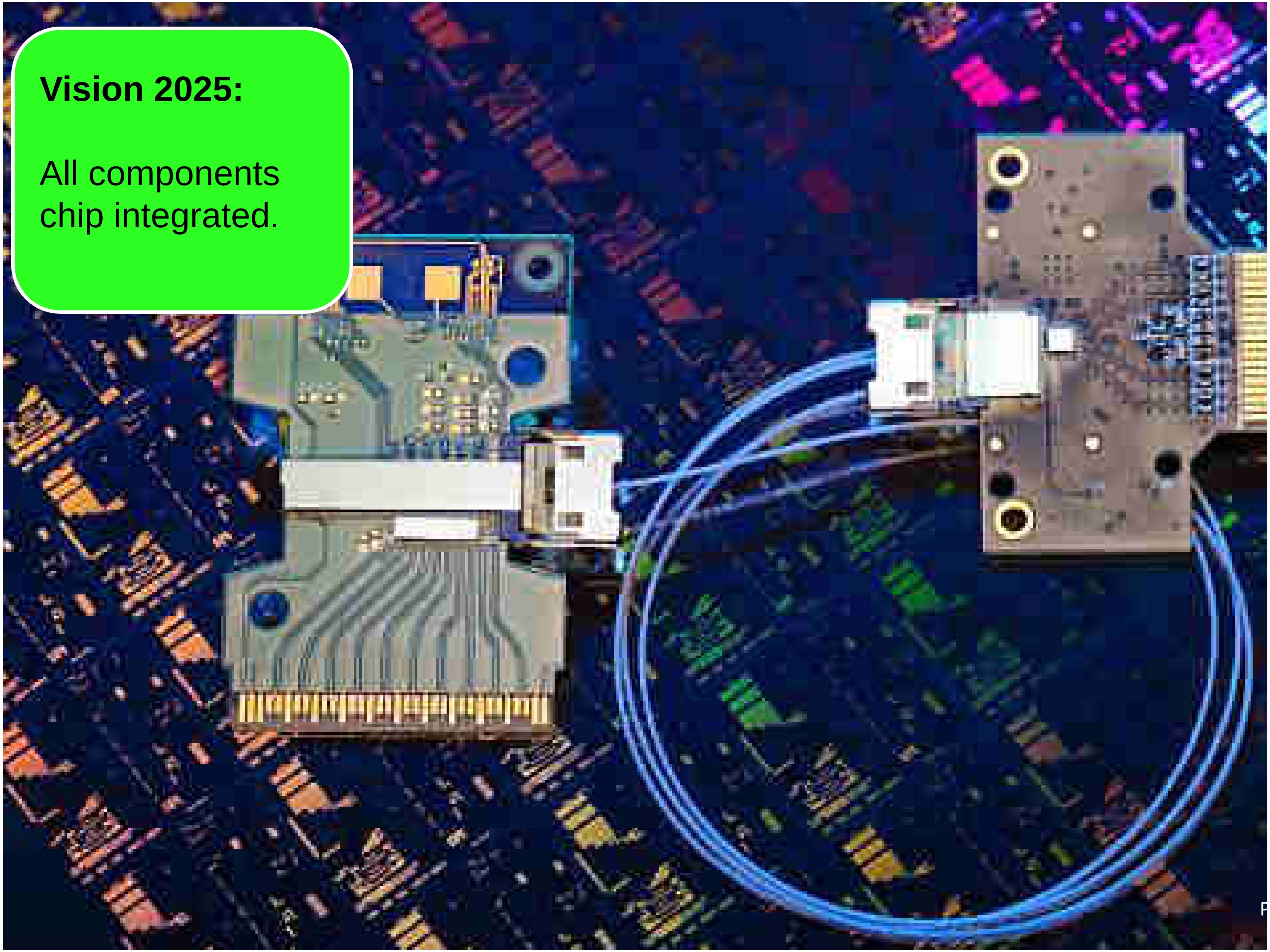
2015:
Cisco CRX 1
Carrier router system.

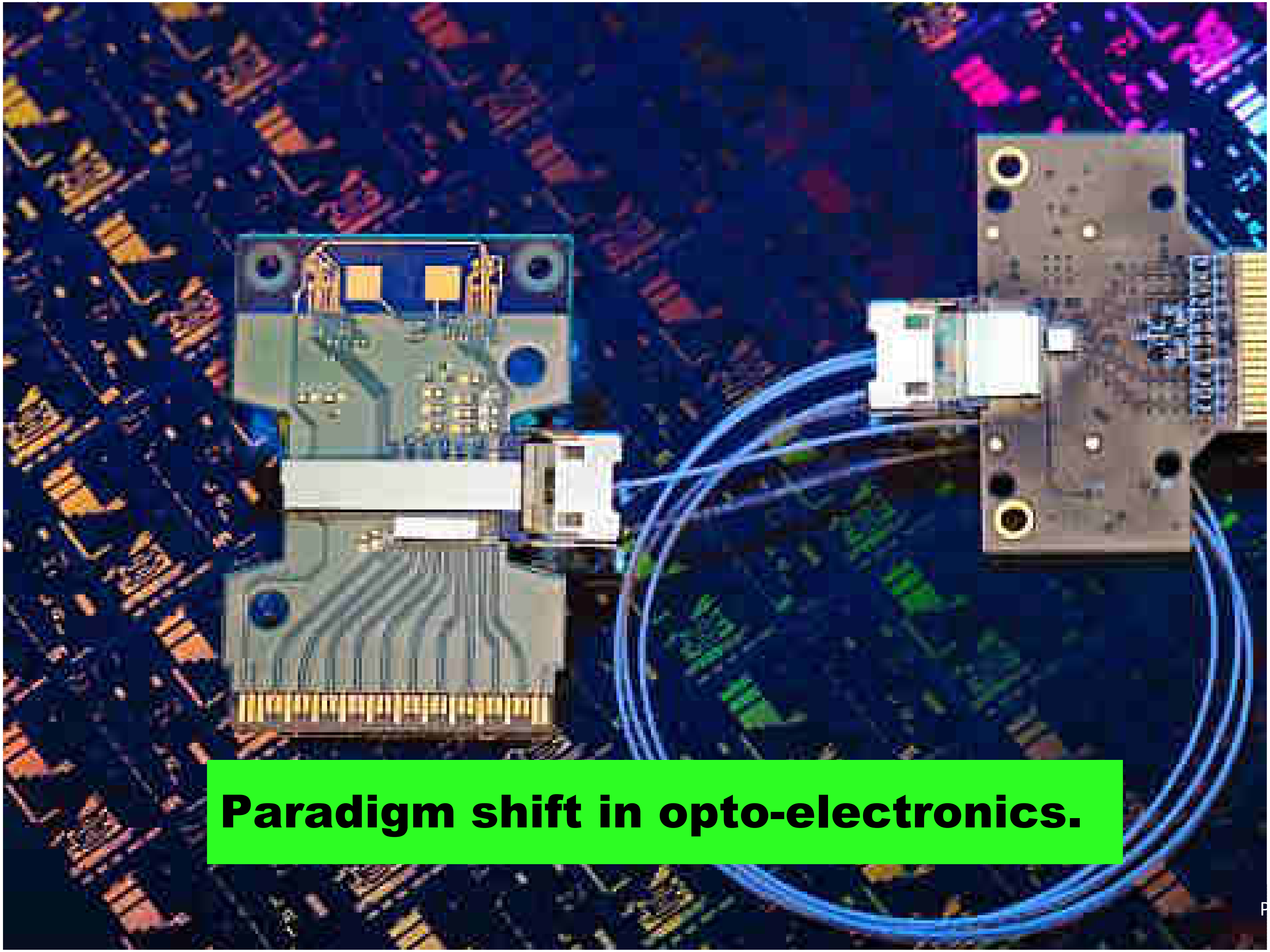
Comprises discrete components.

Pictures: Cisco/Fujitsu/Finisar

Vision 2025:

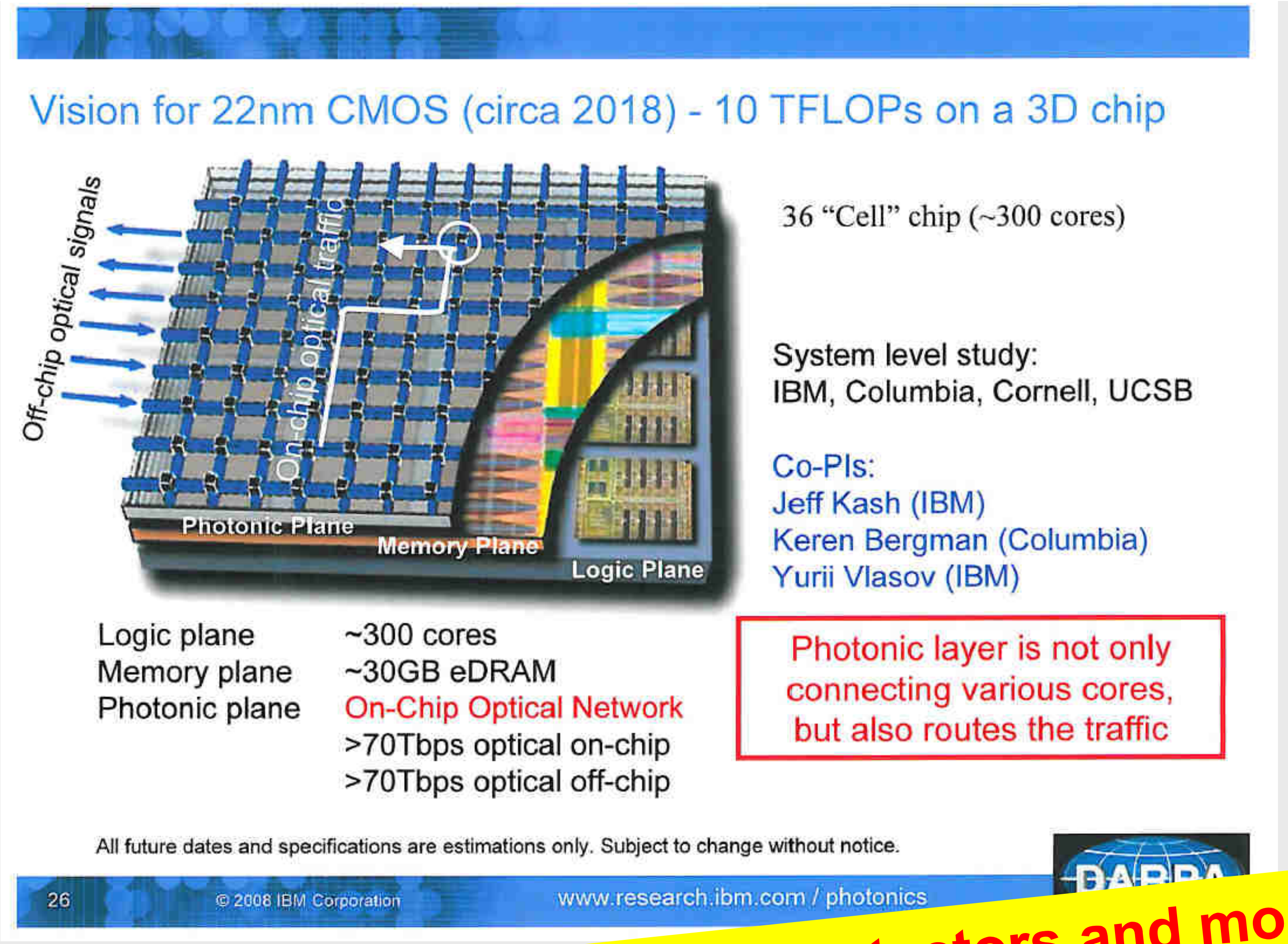
All components chip integrated.





Paradigm shift in opto-electronics.

Extension: Vision for 22 nm CMOS
Convergence Optics / Electronics



Vision for 22nm CMOS (circa 2018) - 10 TFLOPs on a 3D chip

36 “Cell” chip (~300 cores)

System level study:
IBM, Columbia, Cornell, UCSB

Co-PIs:
Jeff Kash (IBM)
Keren Bergman (Columbia)
Yurii Vlasov (IBM)

Logic plane	~300 cores
Memory plane	~30GB eDRAM
Photonic plane	On-Chip Optical Network
	>70Tbps optical on-chip
	>70Tbps optical off-chip

Photonic layer is not only connecting various cores, but also routes the traffic

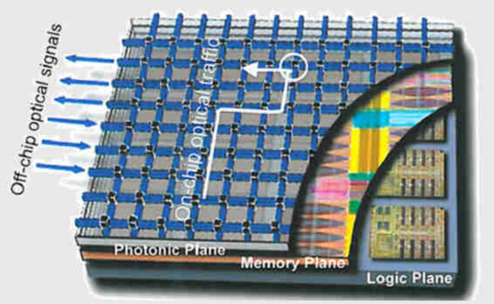
All future dates and specifications are estimations only. Subject to change without notice.

26 © 2008 IBM Corporation www.research.ibm.com / photonics

Current bottleneck: Detectors and modulators

Paradigm shift – Device requirements

Device requirements



Material must enable devices with:

- High bandwidth
- High sensitivity
- High extinction ratio
- Low energy consumption
- Low drive voltages
- Low insertion loss
- Small footprint

Technological requirements

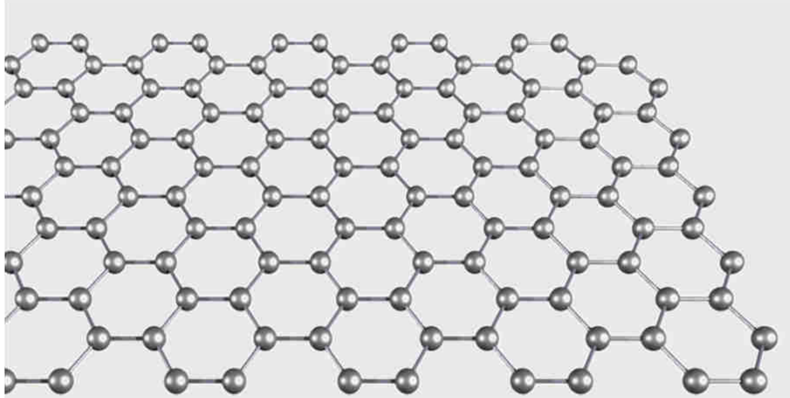
Manufacturing and integration:

- Manufacturing on large scale
- Integration possible
- Process compatibility

Can graphene meet the requirements?

Why graphene?

Intrinsic properties of graphene are promising:



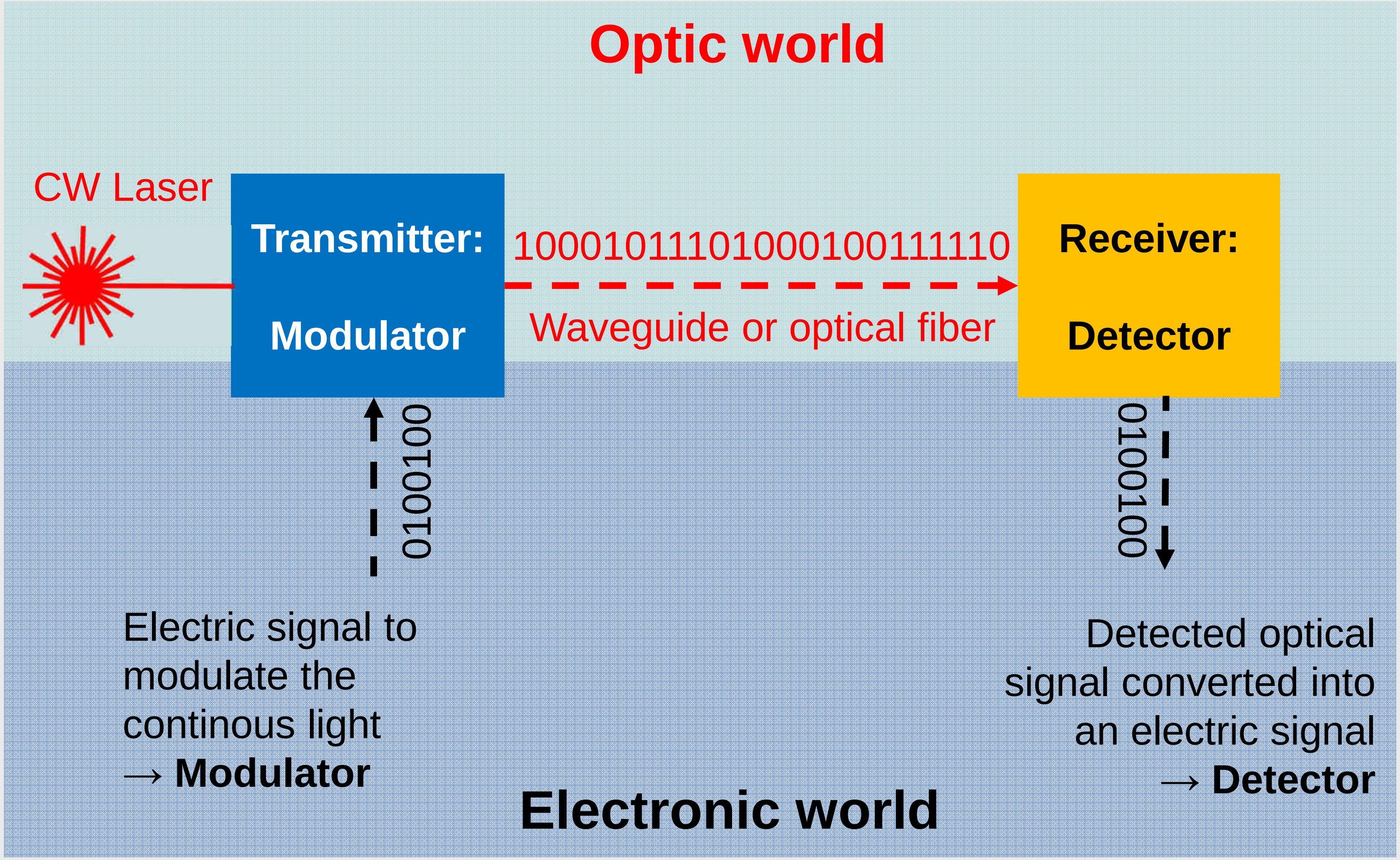
- Ultra broadband interaction (IR-UV)
- High absorption
- High carrier mobility
- Fast relaxation of excited carriers
- Optical properties tunable by gating

Technological compatibility at least in parts demonstrated:

Graphene on
300 mm wafer

- Growth on 12 inch wafer size demonstrated
- Si integration feasible
- Thermally robust (at least to 300°C)

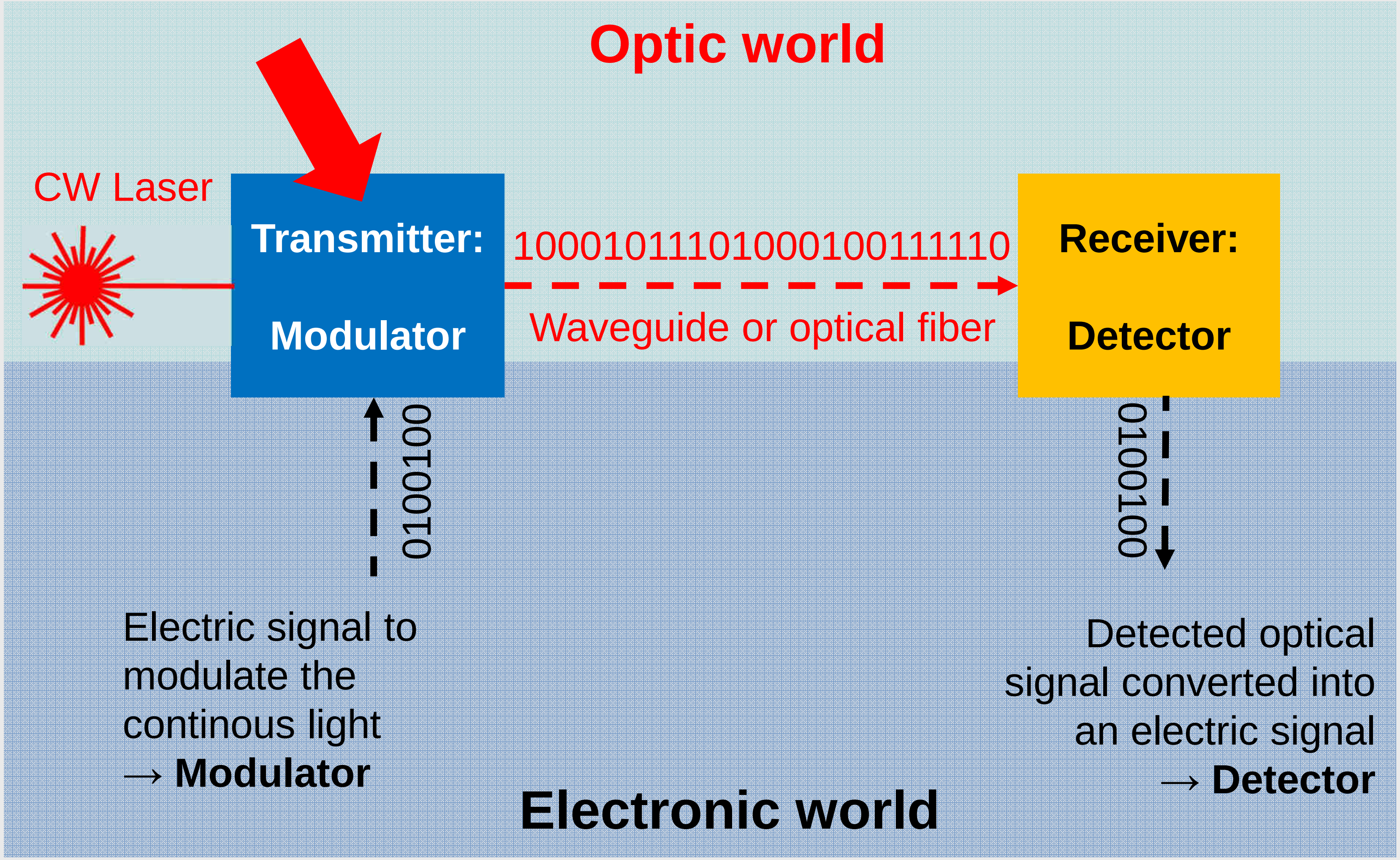
Optical communication schematic



Electric signal to modulate the continous light
→ **Modulator**

Detected optical signal converted into an electric signal
→ **Detector**

Optical communication schematic



Optic world

CW Laser

Transmitter:

Modulator

1000101110100010011110

Waveguide or optical fiber

Receiver:

Detector

0100100

0100100

Electric signal to modulate the continous light → **Modulator**

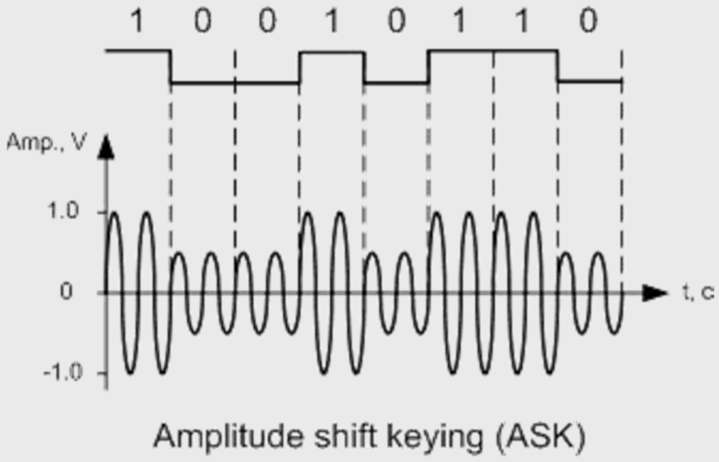
Detected optical signal converted into an electric signal → **Detector**

Electronic world

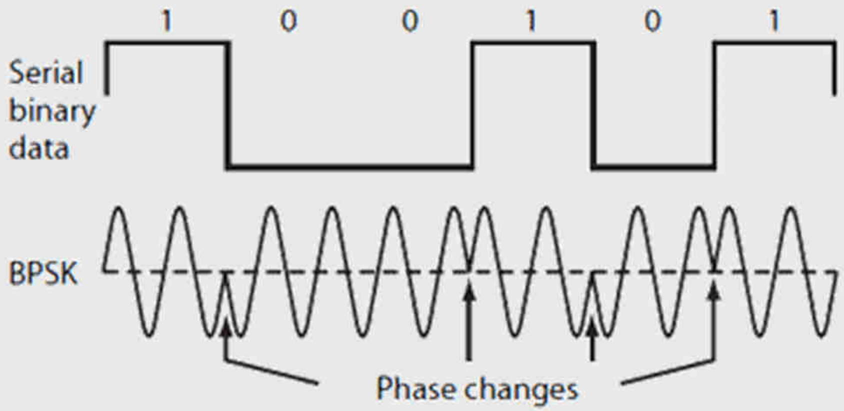
Transmitter:
Phase vs. amplitude modulation

Amplitude shift keying ASK

Binary phase shift keying BPSK



Amplitude shift keying (ASK)

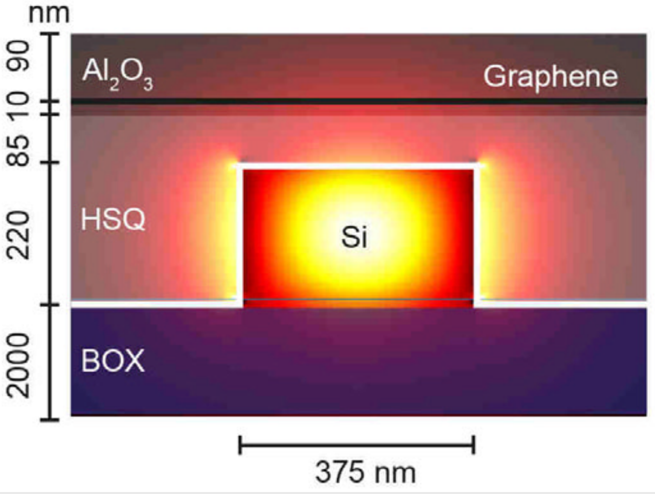


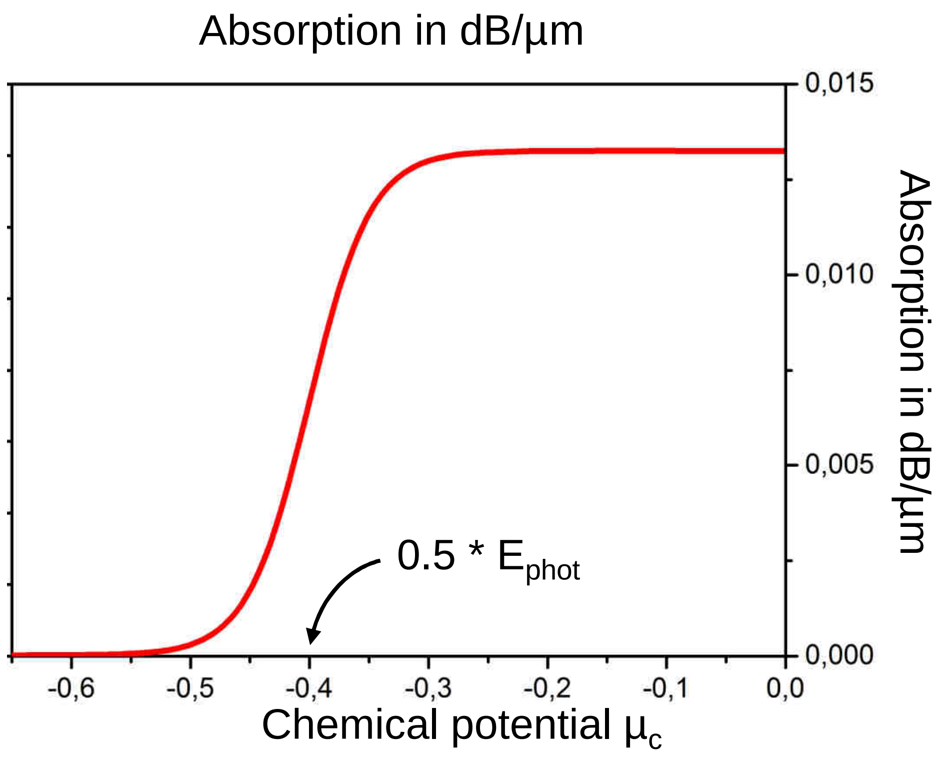
- Simple System
- For low data rates / short distance

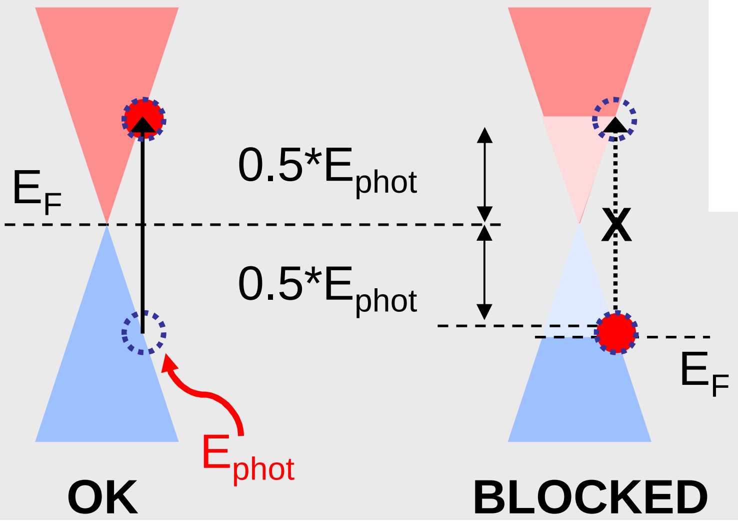
- Complex System
- For high data rates / long distance

2 modulator operation principles.

Simulation of the absorption on Si waveguide



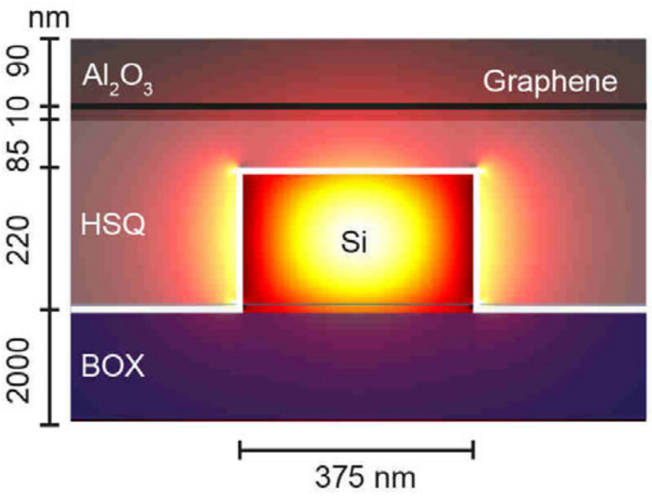


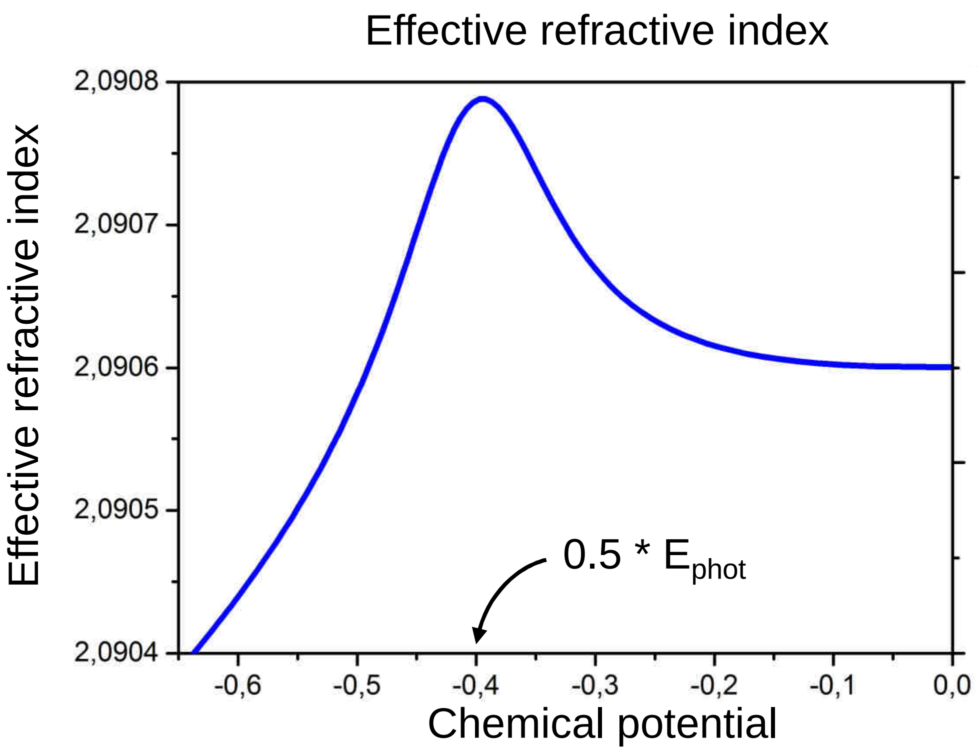


- λ = 1550 nm → E_{phot} = 0.8 eV
- For $|\mu_c| \geq 0.5 * E_{phot}$ states are blocked
→ graphene is transparent

M. Mohsin et al. Scientific Reports 5,10967 (2015)

Simulation of the refractive index on Si waveguide

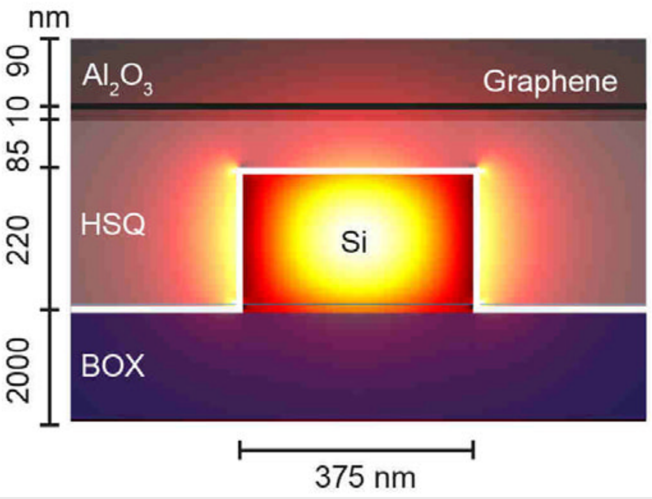


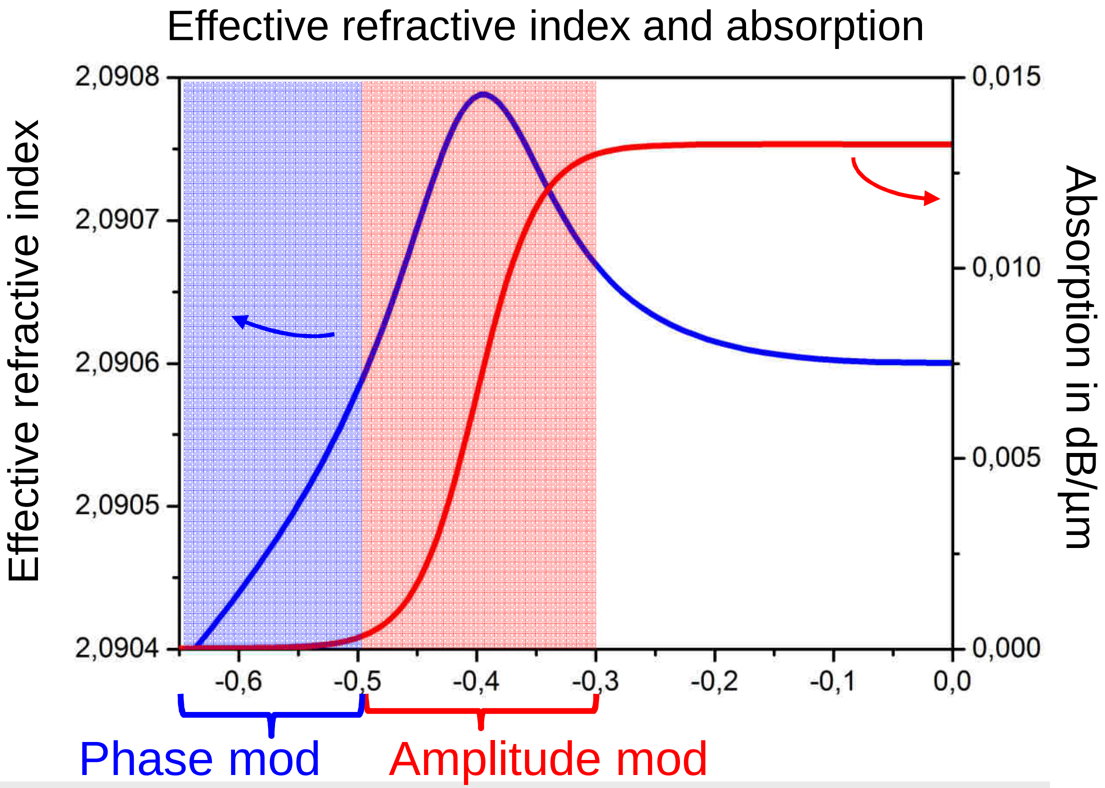


- λ = 1550 nm → E_{phot} = 0.8 eV
- Kramers-Kronig relates the absorption to the refractive index
  → **refractive index is a function of the electro chemical potential**

M. Mohsin et al. Scientific Reports 5,10967 (2015)

Simulation of absorption and refractive index on Si waveguide



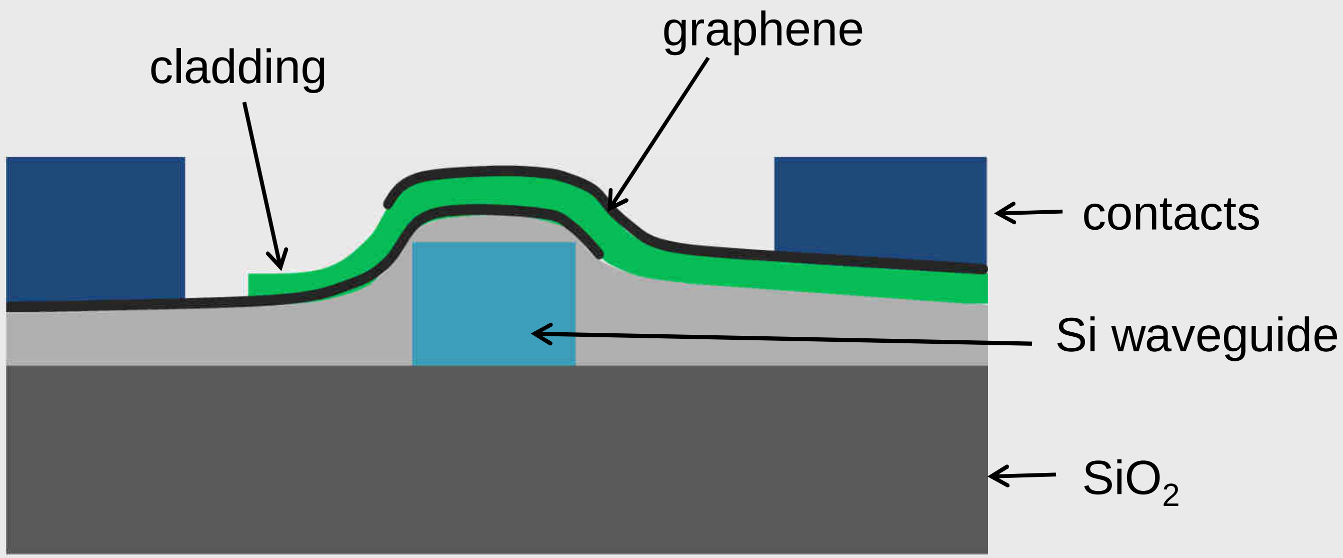


- Refractive index and absorption depend on the chemical potential
- high mobility gives low absorption for µ < -0.4 eV
  preferred for phase modulators.

Phase and absorption modulator realizable

M. Mohsin et al. Scientific Reports 5,10967 (2015)

Absorption modulator schematic

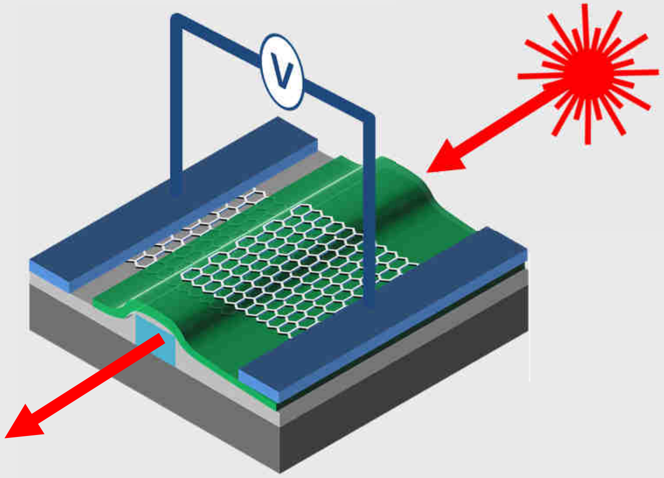


- SOI substrate 220 nm top Si
- Bottom electrode close to the waveguide surface
- Top electrode located in a distance of ~ 90 nm
- The lower electrode is adjusted between transparent and absorbing state

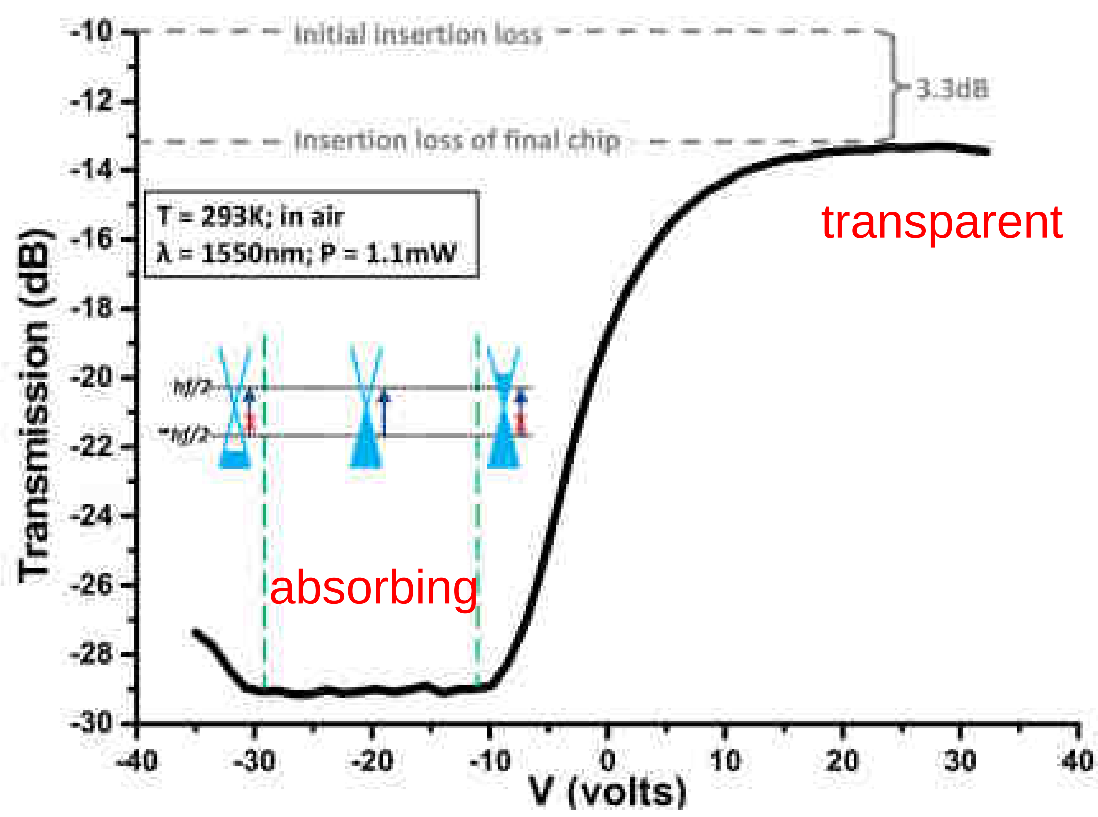
Absorption modulator DC

DC in

light in



light out,
Power measured



transparent

absorbing

High modulation depth, low insertion loss.

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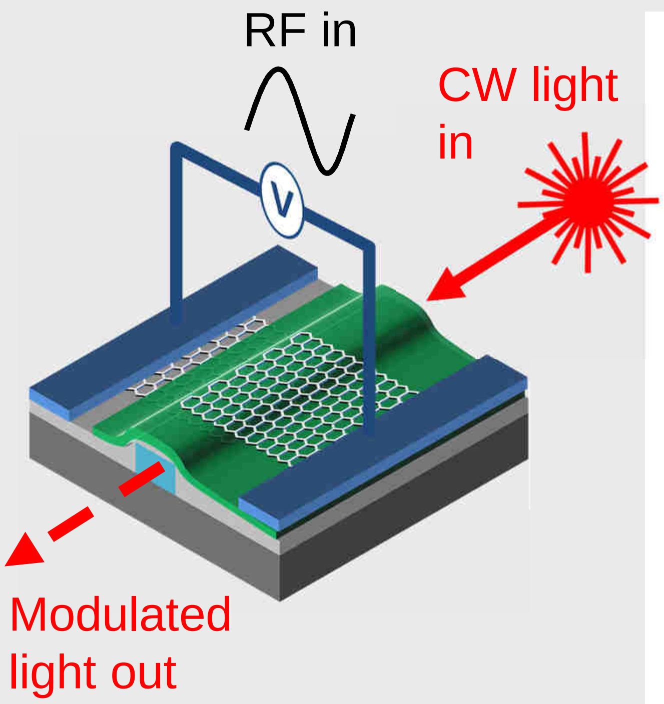
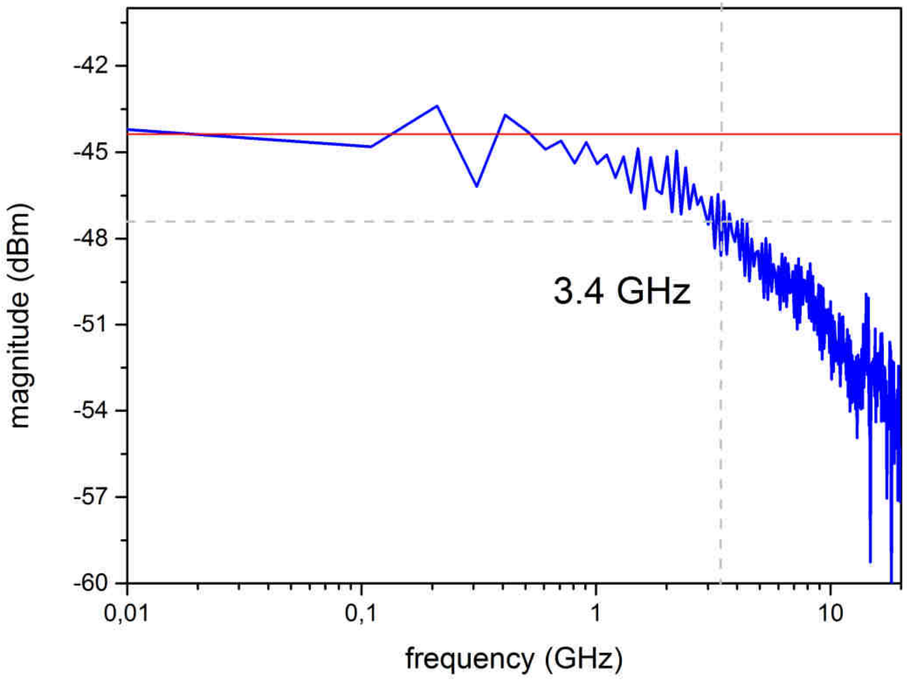
M. Mohsin et al. Optics Express 22, 15292 (2014)

Absorption modulator RF





Bandwidth limiting factors:

- Device geometry graphene electrode overlap ~1.5 µm
- Contact resistance
- No intrinsic limitation

30 GHz already demonstrated by the Lipson Group

C. Phare et al., Nature Photonics 9, (2015)

Absorption modulator comparison

	Graphene[1]	Graphene simulations	GeSi[2]	Si (MZI)[3]	(LiNbO) (~4500 €)
Modulation	**16 dB**	16 dB	**6 dB**	**5.5 dB**	20 dB
Insertion Loss	**3 dB**	<1dB	5 dB	4.2 dB	4 dB
Modulation / IL ratio	**5**	>15	1.2	1.3	5
Length	300 µm	<15µm	30 µm	**5 mm**	**8 cm**
Speed	**3.4 GHz**	**>30 GHz**	**40 GHz**	26.5 GHz	35 GHz

Performance already competitive to SOTA.

1) M. Mohsin et al. Optics Express 22, 15292 (2014)
2) D. Feng et al. Optics Express 20, 2224 (2013)
3) X. Tu et al. Optics Express 21, 12776 (2013)

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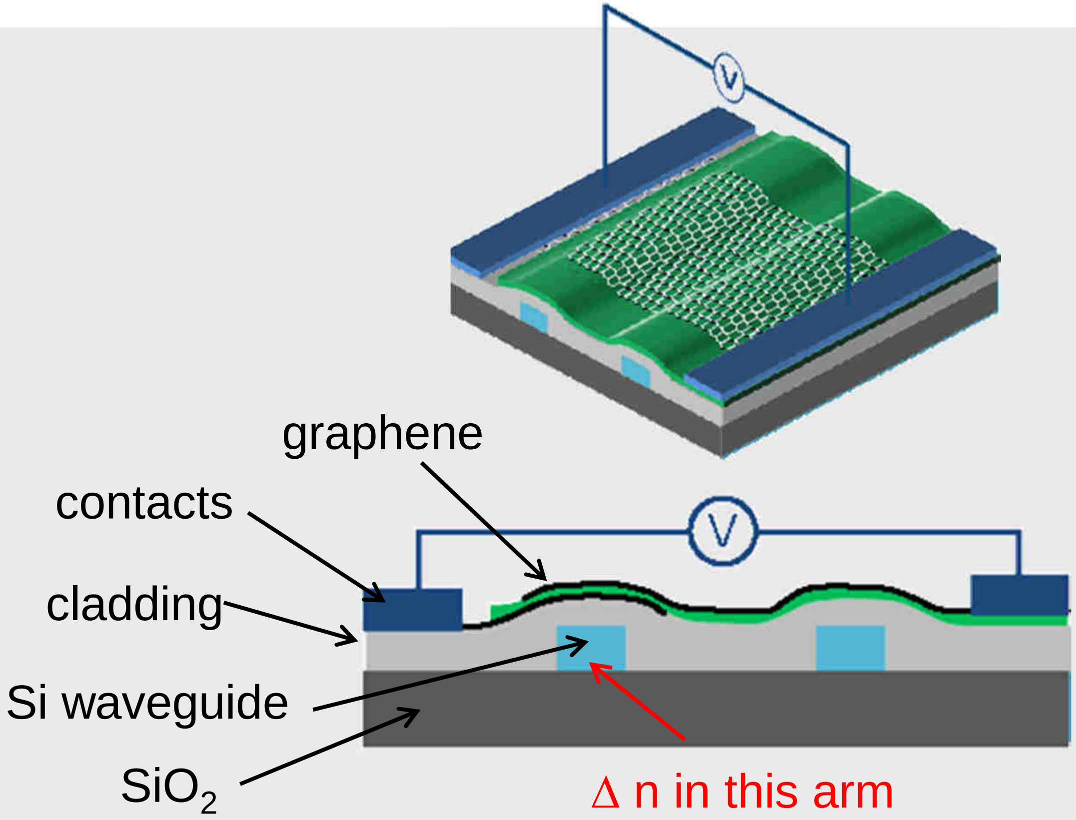
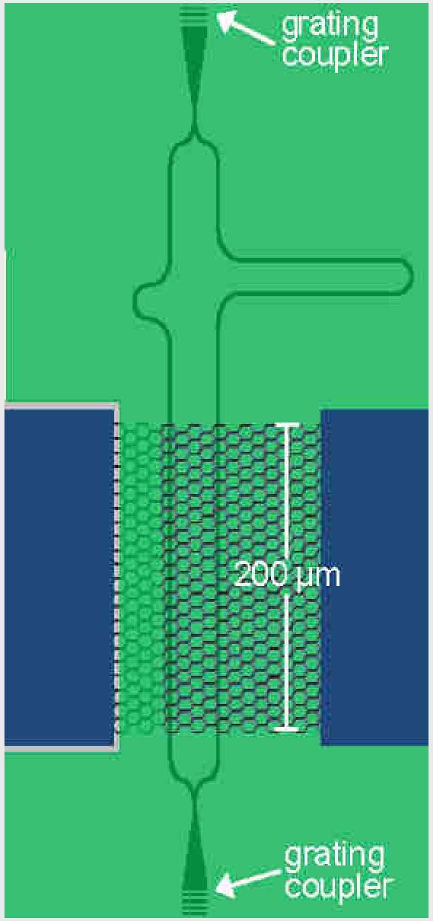
Phase modulator schematic

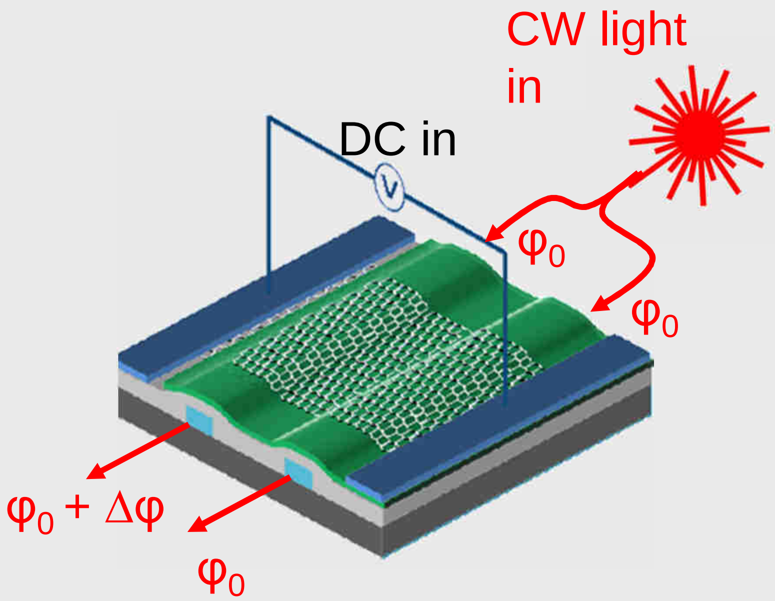


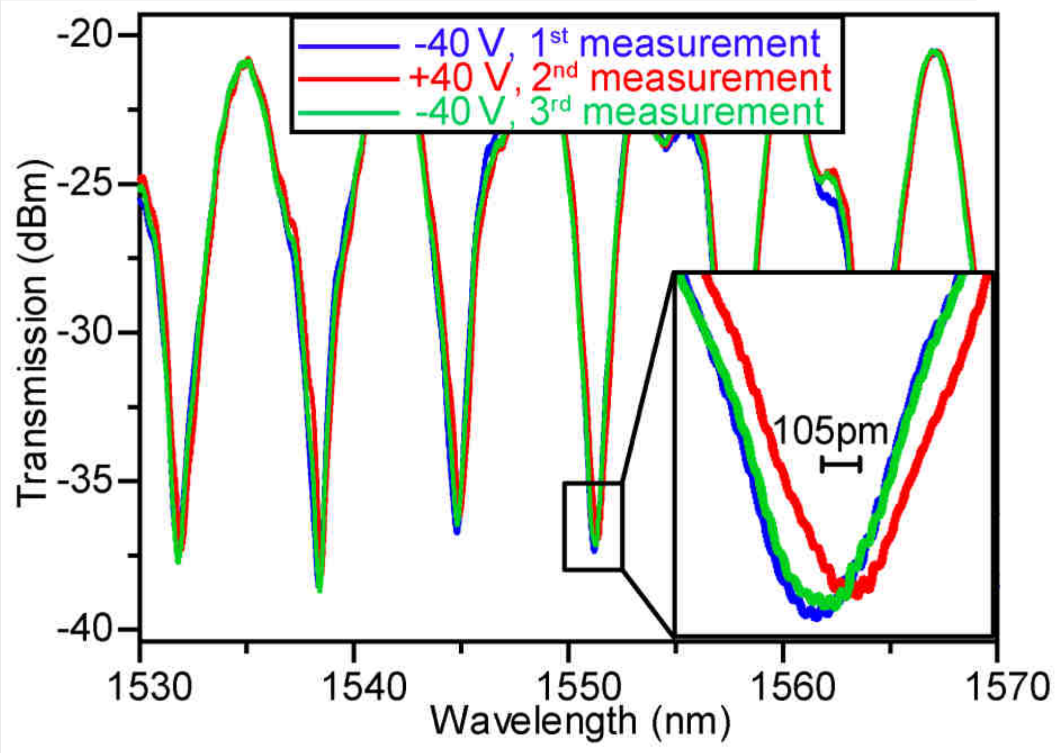


- SOI substrate 220 nm top Si
- Bottom electrode close to the waveguide surface
- Top electrode located in a distance of ~ 90 nm
- The refractive index of the lower electrode is adjusted

M. Mohsin et al. Scientific Reports 5,10967 (2015)

Phase modulator DC measurement

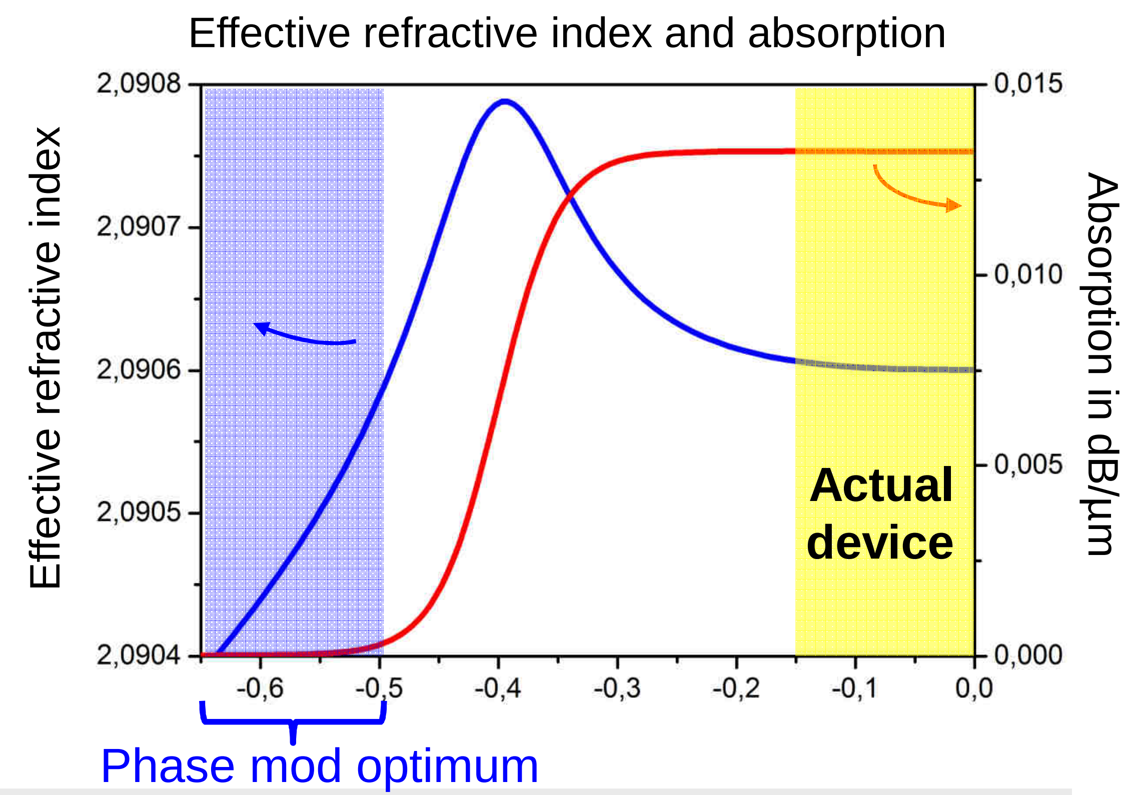




Phase shift observed, prove of concept.

M. Mohsin et al. Scientific Reports 5,10967 (2015)

Explanation of the results



The device was operated in the yellow shaded area.

Problems there:

- High absorption
- Small change of the refractive index

Solution: doping of the device to operate at optimum

M. Mohsin et al. Scientific Reports 5,10967 (2015)

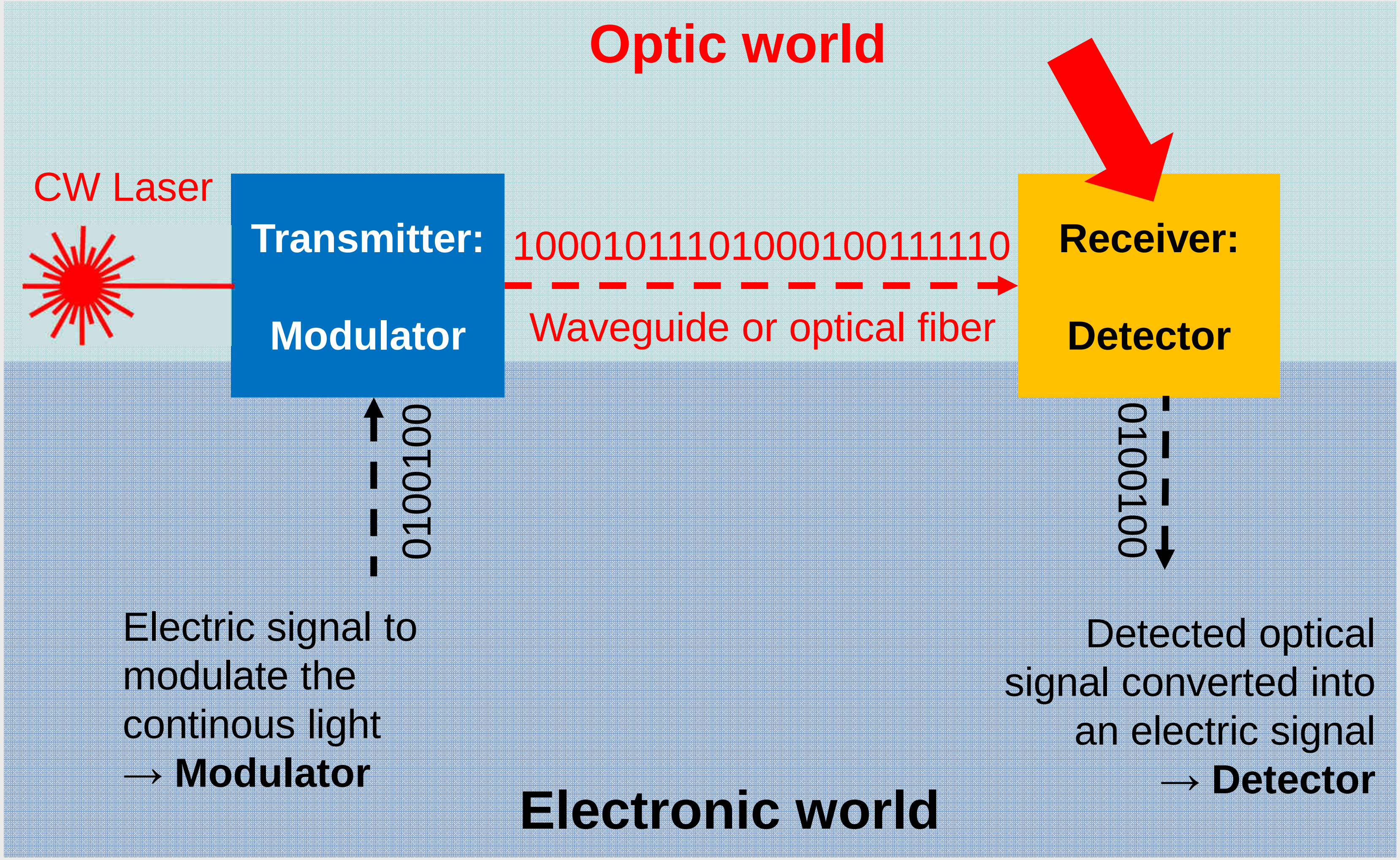
Phase modulator comparison

	Graphene[1]	Graphene Simulations[1]	SISCAP[2]	Si depletion[3]	(LiNbO) (~4500 €)
$V_\pi L$ (Vcm)	30	0.05	<0.2	2.5	~30
Insertion Loss α (dB/cm)	100	<170	65	11	0.6
$V_\pi L\alpha$	3000	<8.3	13	28.5	20

- Operation demonstrated, results far behind SOTA
- Excellent performance expected for high mobility (> 2000 cm²/Vs) and high doping levels > 0.5 eV

1) M. Mohsin et al. Scientific Reports 5,10967 (2015)
2) Webster et al. IEEE Group IV conf (2014)
3) Xiao et al. Optics Express 21, 4116 (2013)

Optical communication schematic



Optic world

CW Laser

Transmitter:

Modulator

1000101110100010011110

Waveguide or optical fiber

Receiver:

Detector

0100100

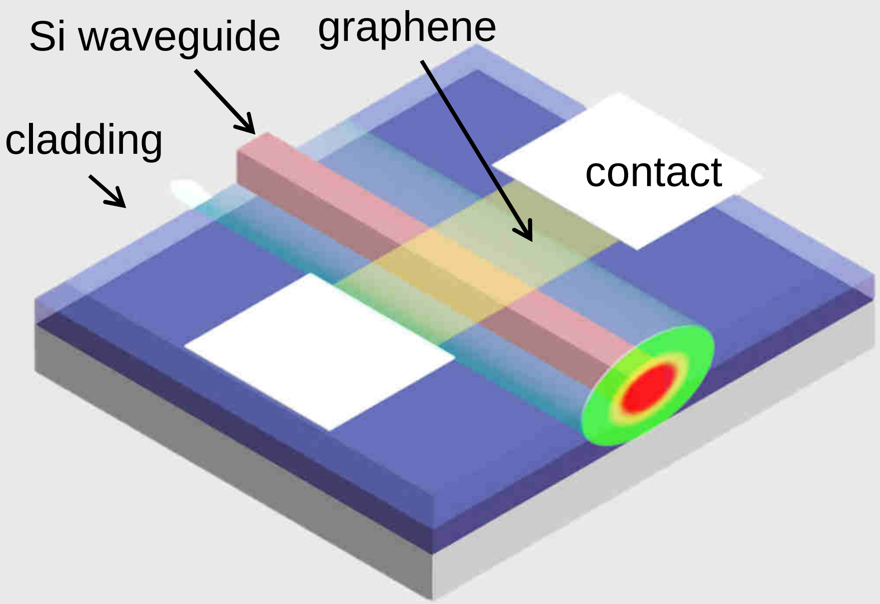
0100100

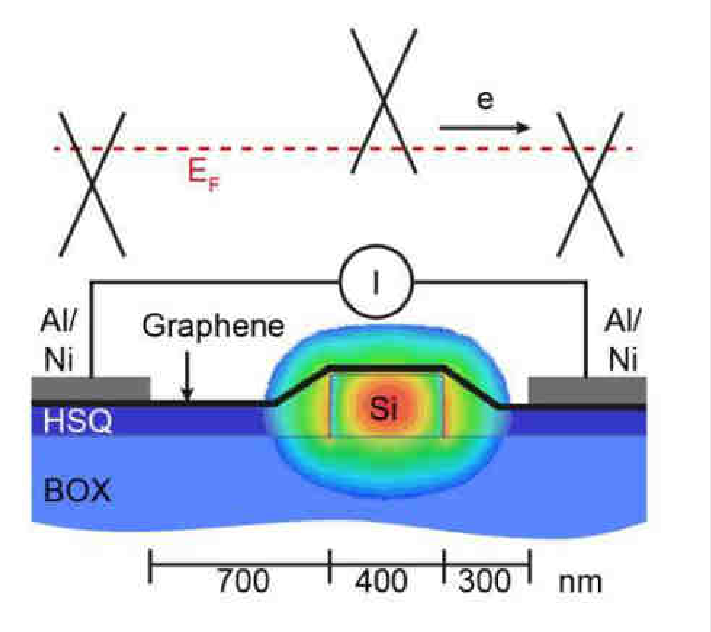
Electric signal to modulate the continous light
→ **Modulator**

Detected optical signal converted into an electric signal
→ **Detector**

Electronic world

Photodetector schematic





- Graphene on Silicon (SOI) waveguide (for λ = 1550 nm).
- Graphene absorption ~35% for l = 30µm.
- CVD grown mono layer graphene (large scale, no flakes).
- Asymmetric contact scheme for net current flow.
- Measured in air and at RT

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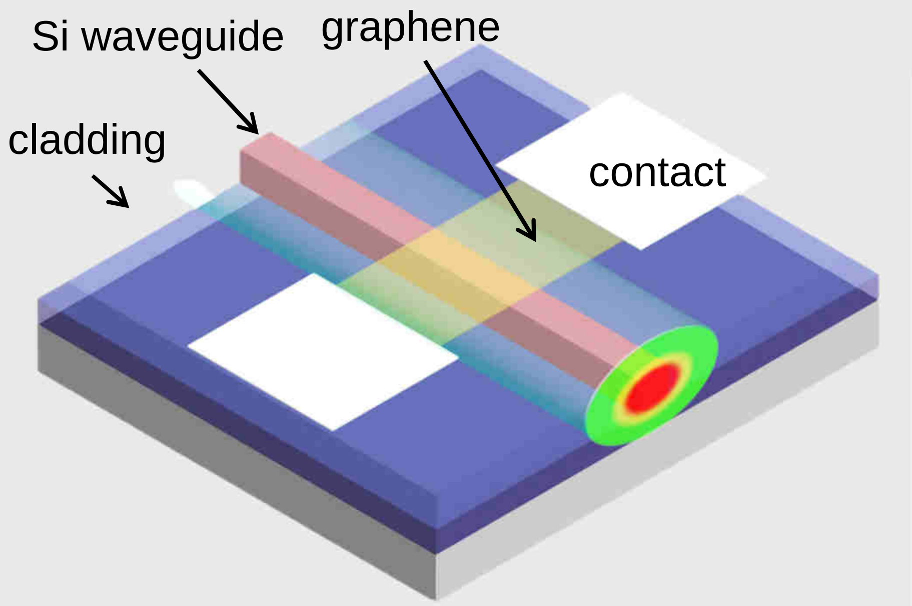
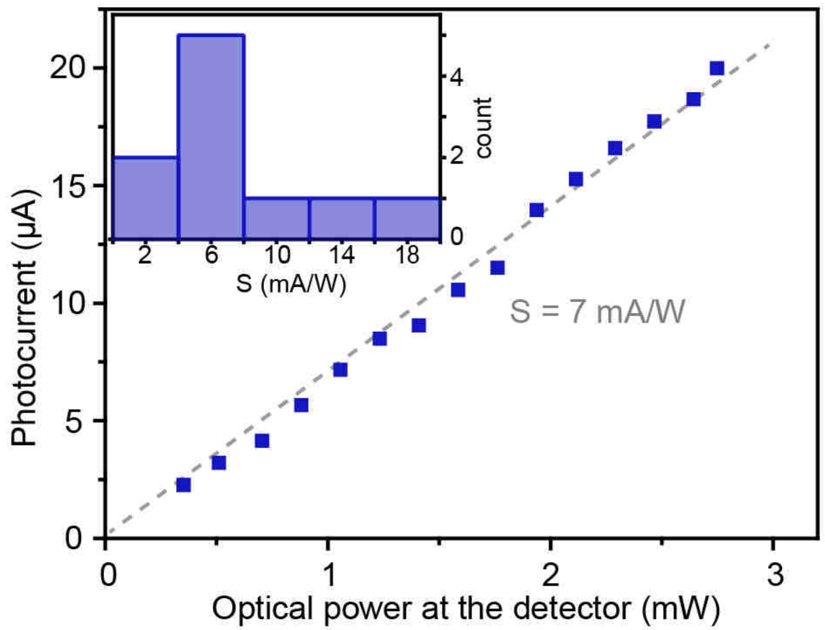
D. Schall et al., ACS Photonics 1, 781(2014)

Bias free response





- 10 detectors on one die
- Linear dependency on optical power
- Extrinsic S = 2..17 mA/W without bias

- Intrinsic S ~ 20…160 mA/W
- Quantum efficiency up to 13 %

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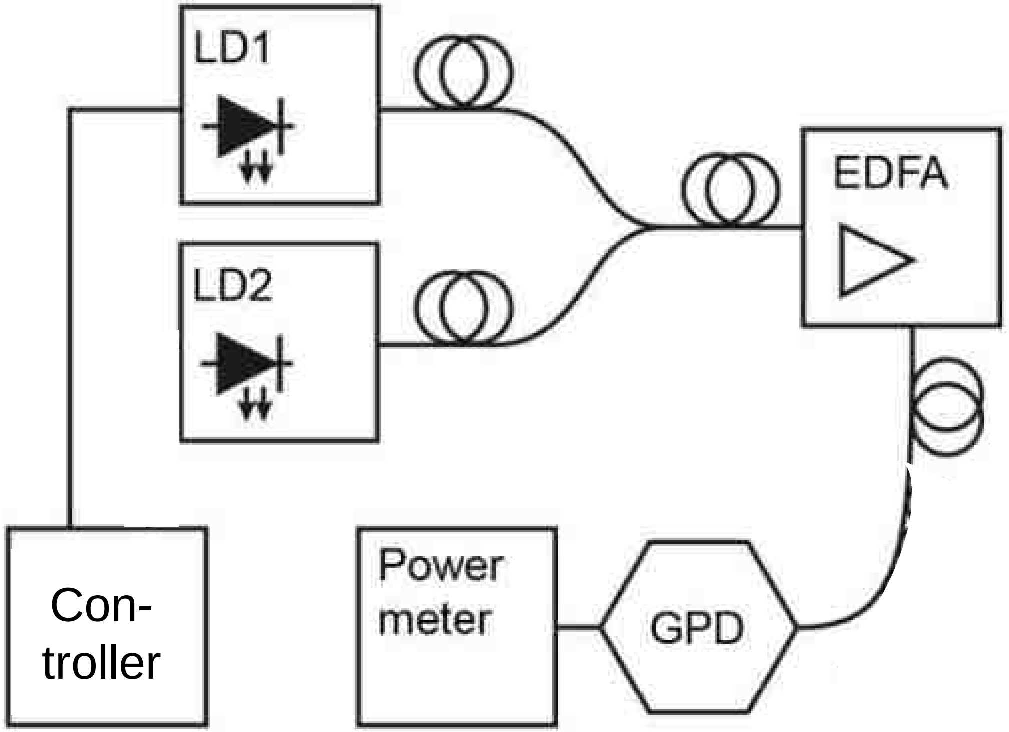
D. Schall et al., ACS Photonics 1, 781(2014)

RF Measurement setup

Signal generation by a heterodyne setup:

- Two laser sources at f1 and f2 (around 1550 nm, ~193 THz)
- Beating frequency
  f = f1 - f2
- f is varied from 1…110 GHz by tuning one laser source



GPD = Graphene photodetector
EDFA = Erbium doped fiber amplifier
LD = Laser diode

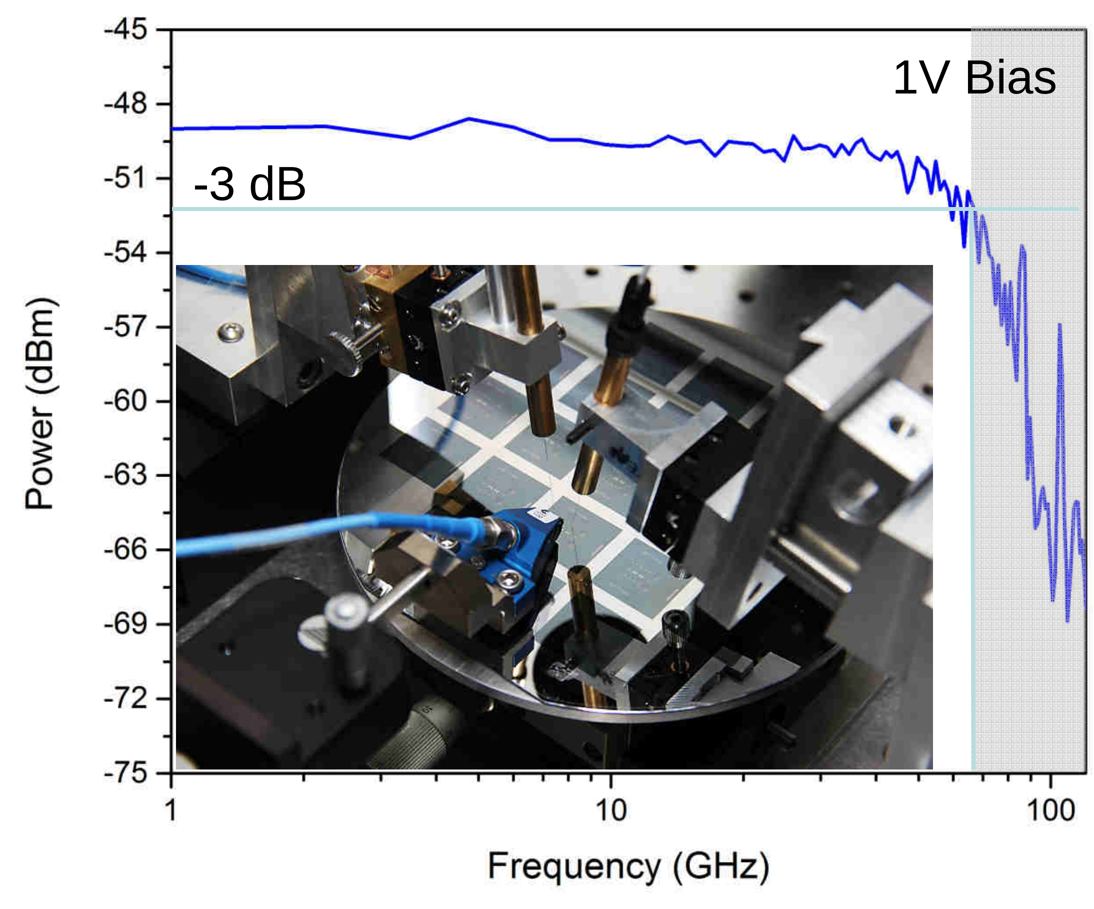
RF measurement up to 110 GHz

Flat up to 70 GHz!

Measurement system designed up to 67 GHz

- Prober ~0.2 dB @ 67 GHz
- Cable 0.8 dB @ 67 GHz
- Bias Tee 0.5 - 1 dB @ 67 GHz

Significant contributions of the equipoment to losses above 67 GHz. Characteristic dominated by system.

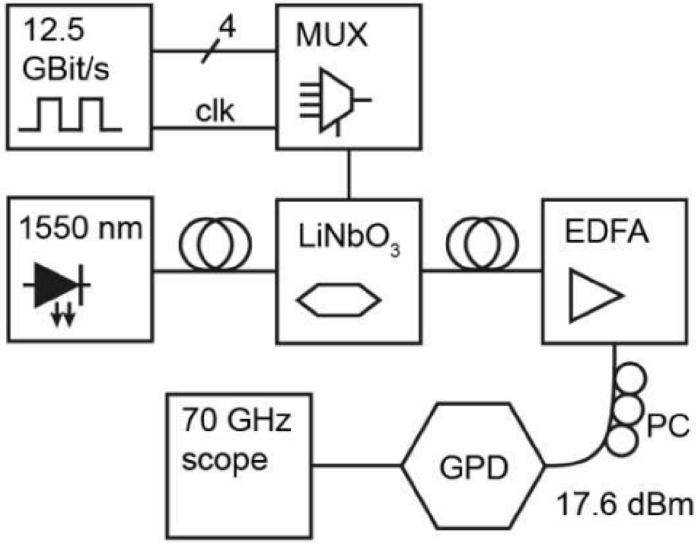


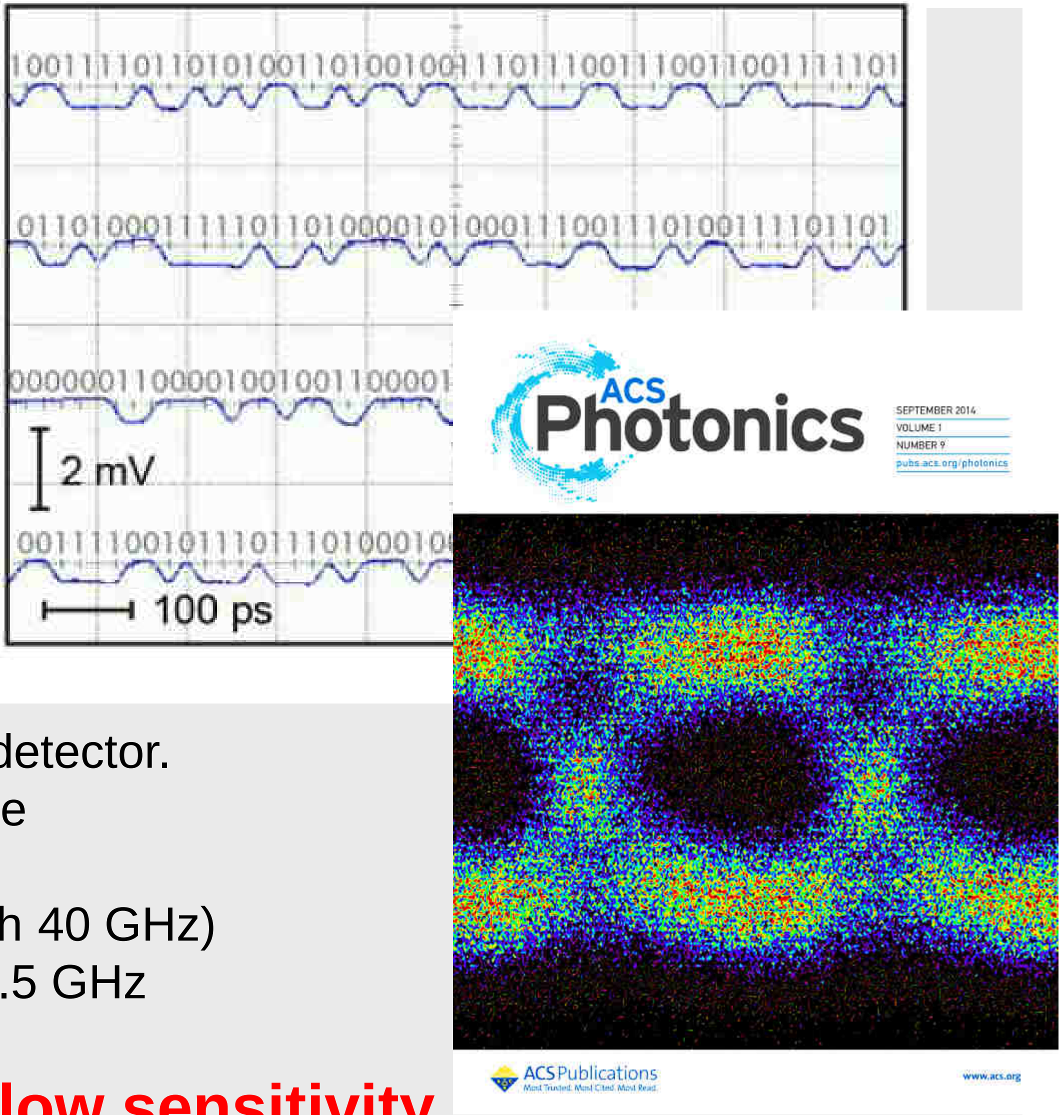
Fabrication entirely on 6”.

Detector bandwidth larger than 70 GHz, Datarate up to 150 GBit/s possible.

AMO unpublished 2015

50 GBit/s data link





- 50 GBit/s bit stream coupled to detector.
- Signal directly displayed at scope
- excellent signal integrity
- System rise time 9 ps (bandwidth 40 GHz)
- Eye diagram for 1 channel at 12.5 GHz

Extremely fast, but very low sensitivity.

D. Schall et al., ACS Photonics 1, 781(2014)

Comparison to SOTA detectors

	Graphene[1]	Graphene potential	Ge[2]	Ge-APD[3]	InP[4]	Phos-phorene[5]
Data Rate GBit/s	50	> 150	40	10	160	3
Sensitivity A/W	0.01 .. 0.1	0.5	0.8 .. 1	10	0.6	0.7
Wafe-scale integration	Not perfect but feasible	OK	OK	OK	NO	Not yet

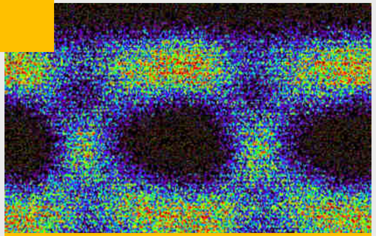
Graphene PDs become relevant for applications, if sensitivity is increased.

1) Schall et al. ACS Photonics 1, 781 (2014)
2) Vivien et al. Optics Express 20, 1096 (2012)
3) Virot et al. Nature Comm. 5, 4957 (2014)
4) Heinrich Hertz-Institute Berlin (2015)
5) Youngblood et al. Nature Phot. (2015)

Paradigm shift – Requirements CHECK

Device requirements


Low loss


High speed

Parameter	Det	Mod
High bandwidth	🟩	🟧
High sensitivity	🟧	
High extinction ratio		🟩
Low energy consumption	🟩	🟧
Low drive voltages	🟩	🟧
Low insertion loss		🟩
Small footprint	🟩	🟩

Technological requirements


300 mm growth


6“ integrated

Parameter	
Manufacturing on large scale	🟩
Integration possible	🟩
Process compatibility	🟧

🟩 OK   🟧 Not yet but feasible

Summary

The EO properties of graphene are very promising for optical interconnects:

- Graphene based photodetectors show ultrafast response; sensitivity is currently a major limitation.
- Graphene based amplitude modulators are already outperforming competing technologies in most parameters; the limited speed is not an intrinsic problem (30 GHz already demonstrated).
- Phase modulators based on graphene are promising from a theoretical point of view; large gap between experiment and theory.

► Graphene could become the missing link for the convergence of electronics and optics and enable the next paradigm shift.

AMO

Acknowledgement

AMO Graphene and Photonics teams

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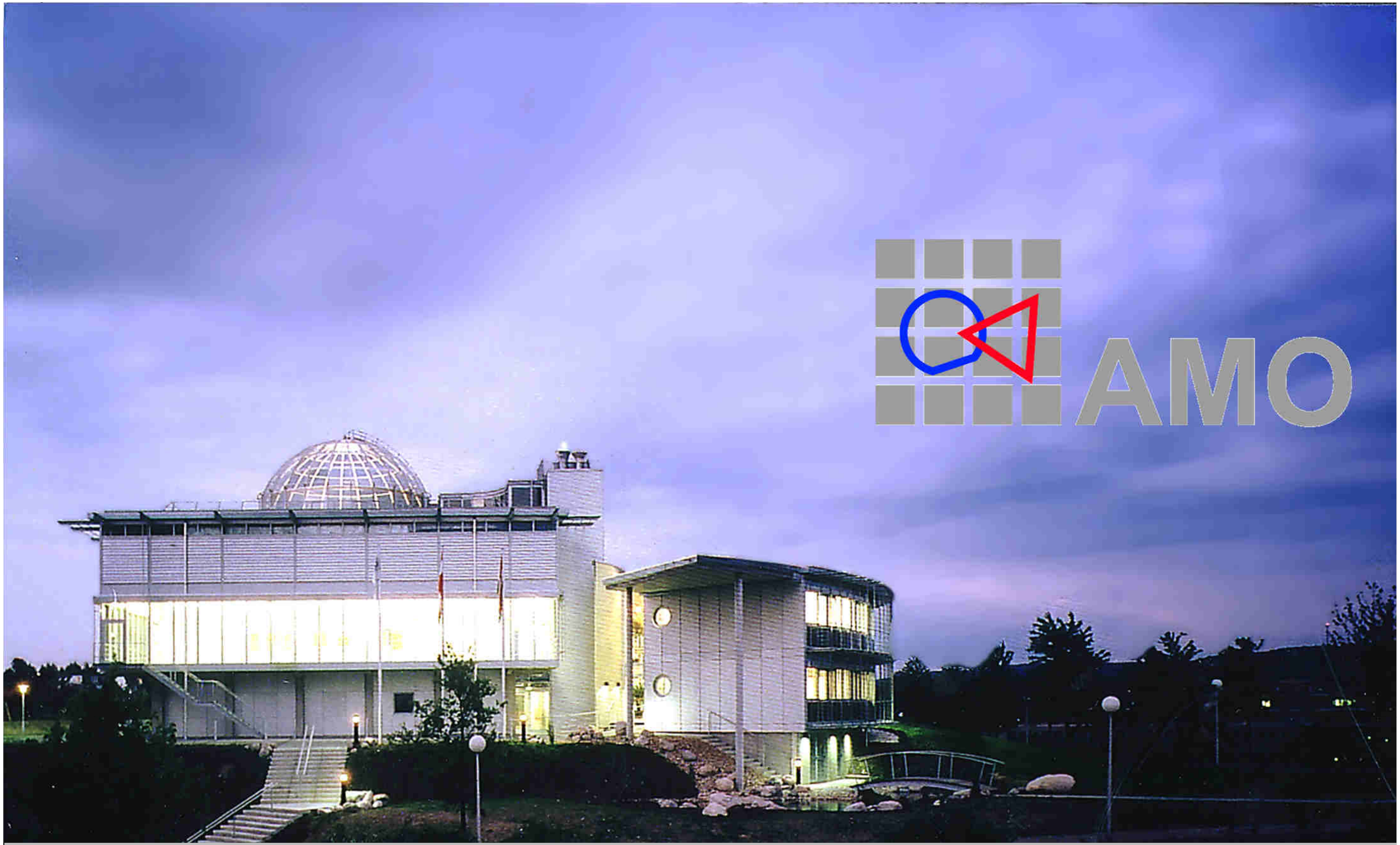
Thomas Mueller, TU Vienna
Christoph Stampfer, RWTH Aachen
Stephan Hofmann, UCAM
David Jimenez, UAB
Gianluca Fiori, Pisa
Gerd Bacher, Duisburg Essen

GRAPHENE FLAGSHIP

GRAFOL

SEVENTH FRAMEWORK PROGRAMME

Deutsche
Forschungsgemeinschaft
DFG



Thank you for your attention.