UCL DEPARTMENT OF ELECTRONIC AND ELECRICAL ENGINEERING
INTEGRATED GRADUATE DEVELOPMENT PROGRAMME
MSC TELECOMMUNICATIONS

Optical Receivers

most vulnerable part of system

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Agenda

- Receivers and detectors
- Key receiver parameters
- Noise and sensitivity calculation
- Examples

Basic definition

- The optical receiver aims to create an electronic replica of the received optical signal (either fro, a fibre, free-space link or inter-chip) with minimum addition of noise or distortion
- The minimum receiver configuration contains a photodetector and amplifier(s). Digital receivers contain timing circuitry
- It is often argued that the received is the weakest link in the fibre system chain

OKI 10 Gbit/s receiver

Direct Optical Detection - I

- Incident optical power, P_{opt} [Watts = Joules/s], corresponds to P_{opt}/hf photons/s since each photon has energy $hf = hc/\lambda$

  h is Planck's constant = 6.626×10^{-34} Joules.s
  = 4.135×10^{-15} eV.s

- Each photon releases on average $\eta_q<1$ electrical carriers (electron-hole pair), giving an electron rate of $\eta_q P_{opt}/hf$

η_q is termed the quantum efficiency and is a function of wavelength (or frequency)

- Each electron carries e (or q= 1.6022×10^{-19} coulombs) of charge, so that the rate of flow of charge (current) is known as the *photocurrent* $I_p = \eta_q P_{opt} e/hf$ [Coulomb/s=Amps]

Noting that $c = f\lambda$, this can be written as: $I_p = \eta_q P_{opt} e\lambda/hc$

Direct Optical Detection - II

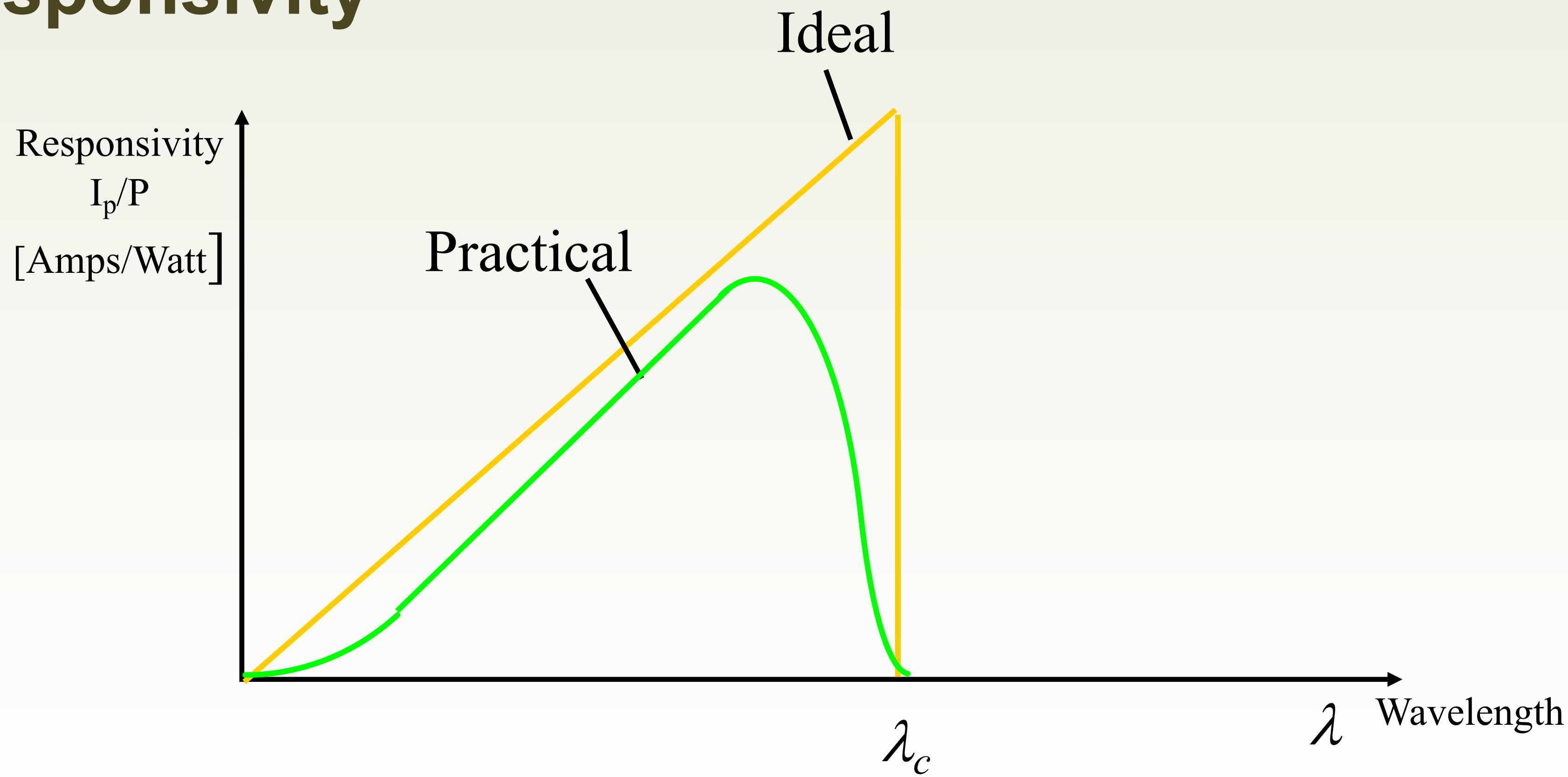
$$I_p = \eta_q P_{opt} e\lambda/hc$$

- The Responsivity $\mathcal{R}$ is defined as I_p/P_{opt} [A/W]

  Hence $\mathcal{R} = \eta_q e\lambda/hc$
- The responsivity is more of a practical engineering measure than η_q
- $\mathcal{R}$ increases with λ, since a given incident power corresponds to a higher photon rate at longer wavelengths where each photon carries less energy
- The long wavelength cut-off, λ_c, corresponds to a wavelength beyond which the photons do not have sufficient energy to raise electrons from the valence to the conduction band, η_q becomes zero

Responsivity

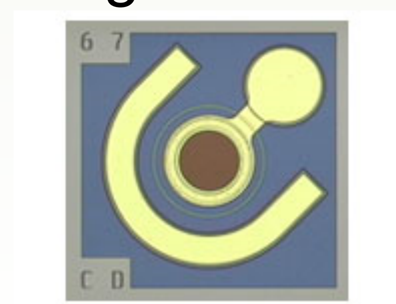
Typical material in photodiode is GaAs, InP, InAIGaAs



- Responsivity peaks near the long wavelength cut-off (Band-edge)
- Responsivity falls off rapidly to zero at $\lambda = \lambda_c$

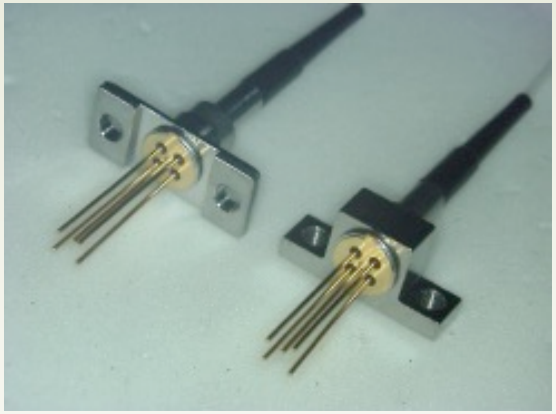
Types of photodetectors (photoelectric)

- p-i-n Photodiodes
  - Most commonly used, effectively a modified pn junction with an intrinsic region between the p and n regions.
- Avalanche Photodiodes (APD)
  - A more complex structure requiring large bias to create an avalanche of carriers that will amplify the generated photocurrent



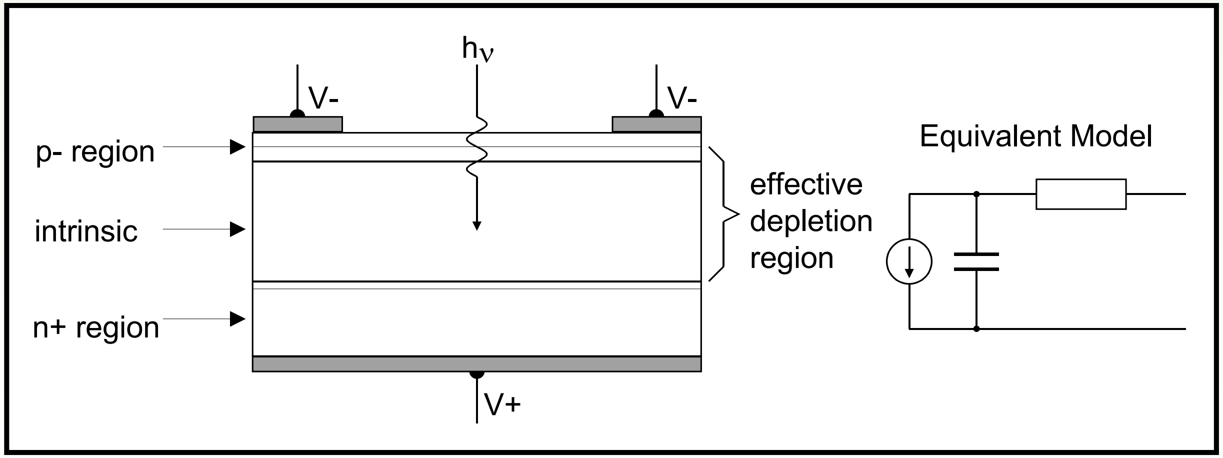
The p-i-n diode

quantum efficiency, responsitivity, dark current are three most important parameters we should consider



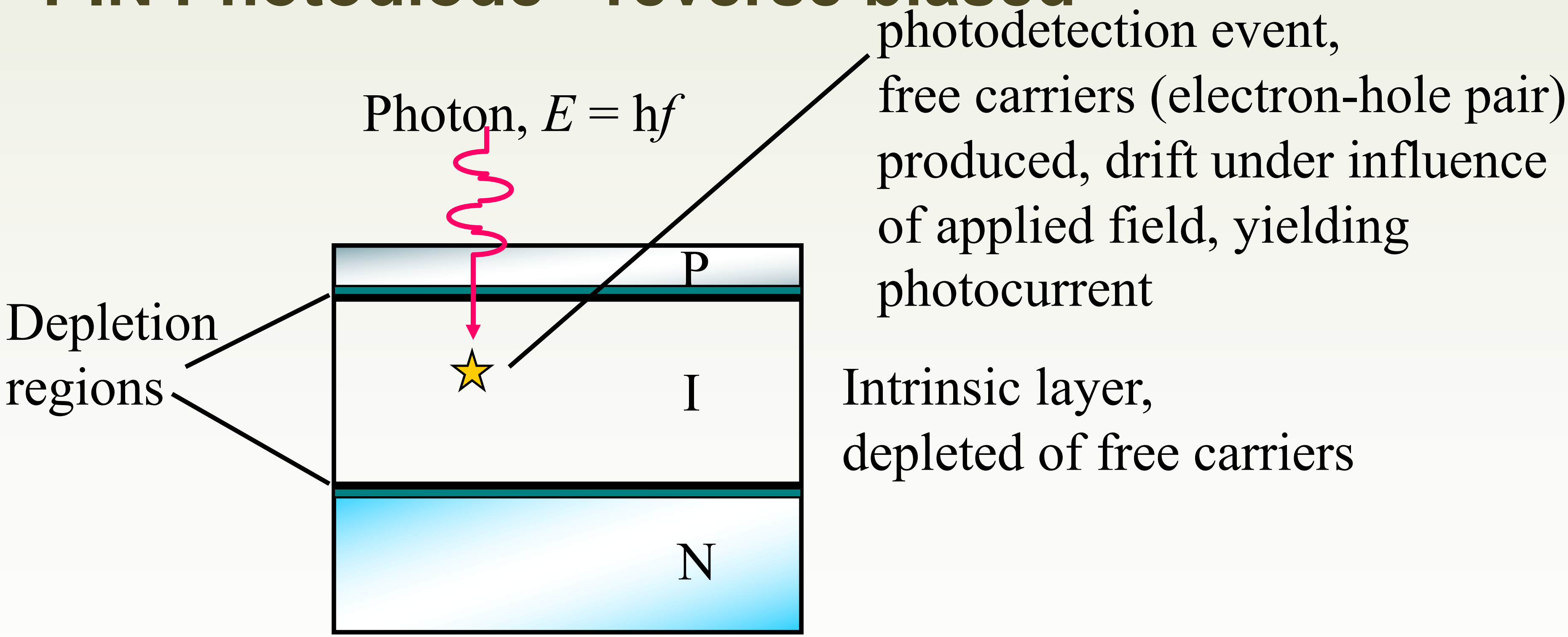
Key characteristics

- The quantum efficiency and Responsivity (note λ dependence)
- The equivalent capacitance
- The dark current



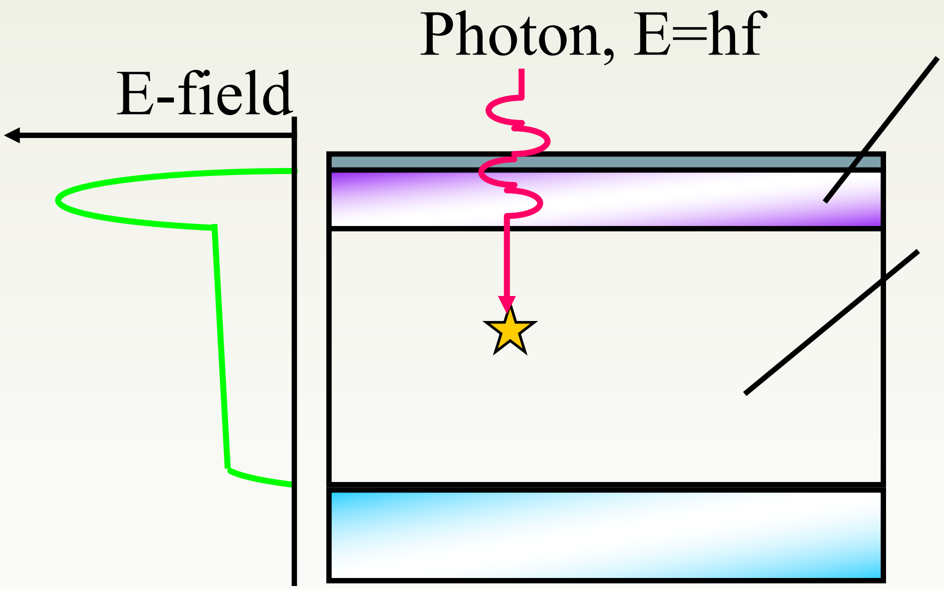
The APD has a more complex structure. One of its important parameters is its internal gain vs. bias voltage

PIN Photodiode - reverse biased



- Dominant speed limiting factors are *RC* time constant and transit time for carriers to drift across the *I* (+depletion) region; thick *I* region means *C* is small, but transit time T_r increases

Avalanche Photodiode



High E-field gain region, where carrier multiplication occurs

Moderate E-field absorption region, where photons are detected and ‘primary’ carriers produced and then ‘drift’, the more strongly ionising moving towards the gain region and being subjected to impact ionisation, providing carrier multiplication gain

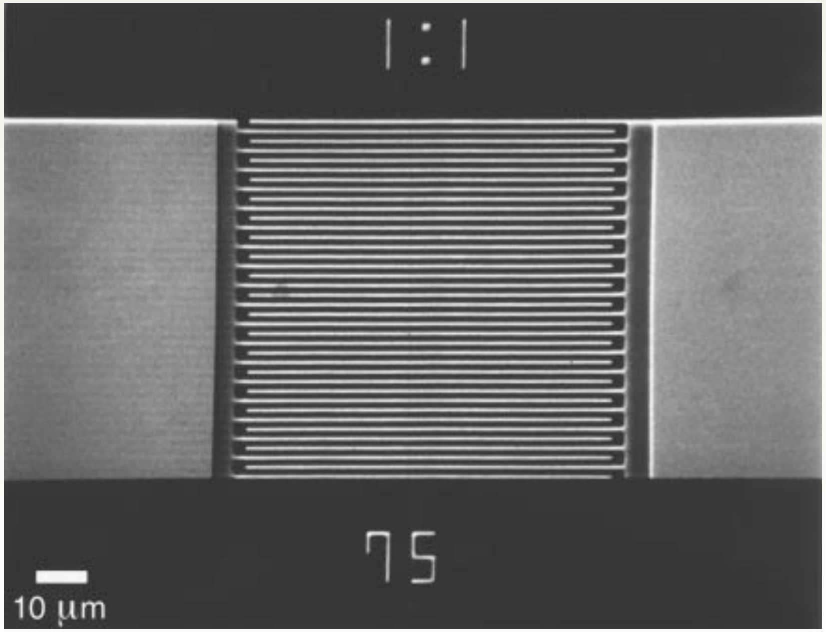
Quite noise because it quite random

- Silicon APDs provide high sensitivity and low noise for first-window systems
- Longer wavelength systems require germanium or III-V APDs, which cannot match the noise performance of silicon APDs

MSM Photodetectors

Metal-Semiconductor-Metal photodetectors

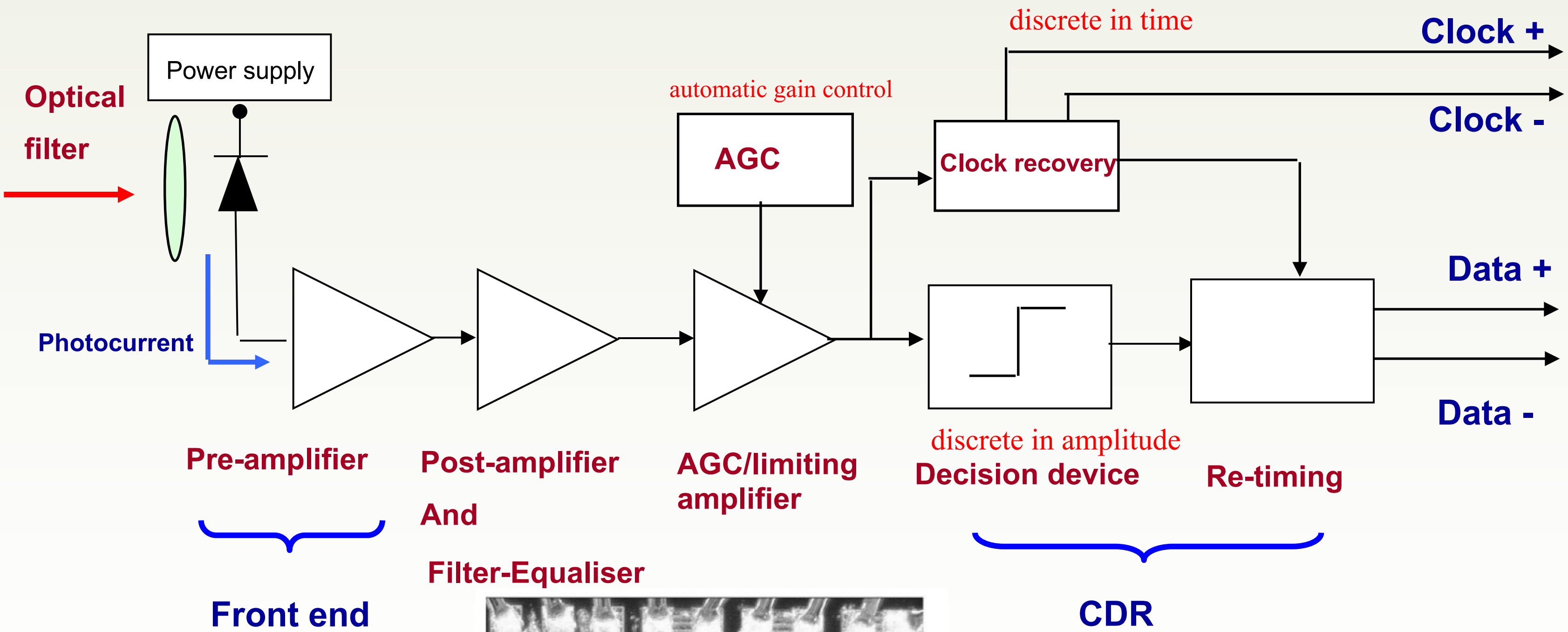
- Used in integrated circuits (OEICs)
  - A comb-like structure with closely spaced metal electrodes (transparent fingers) on top of the semiconductor substrate
  - Very high bandwidths are possible, operation is transit time limited.(C_{det}~10s fF)
  - Travelling wave MSM detectors can achieve BW in the 100s GHz



From Wei Gao *etal*, IEEE Trans. Electron Devices, Dec 1997

A *typical* receiver architecture (digital)

The main components of a receiver are as in the diagram below. The rest of the lecture is dedicated to explain the function of these.



2.5 GBit/s Integrated receiver

Chen and Huang 2007 (Taiwan)

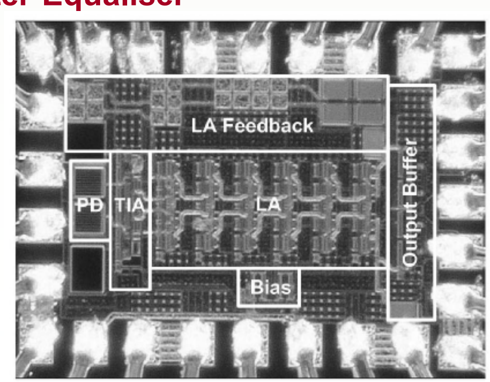
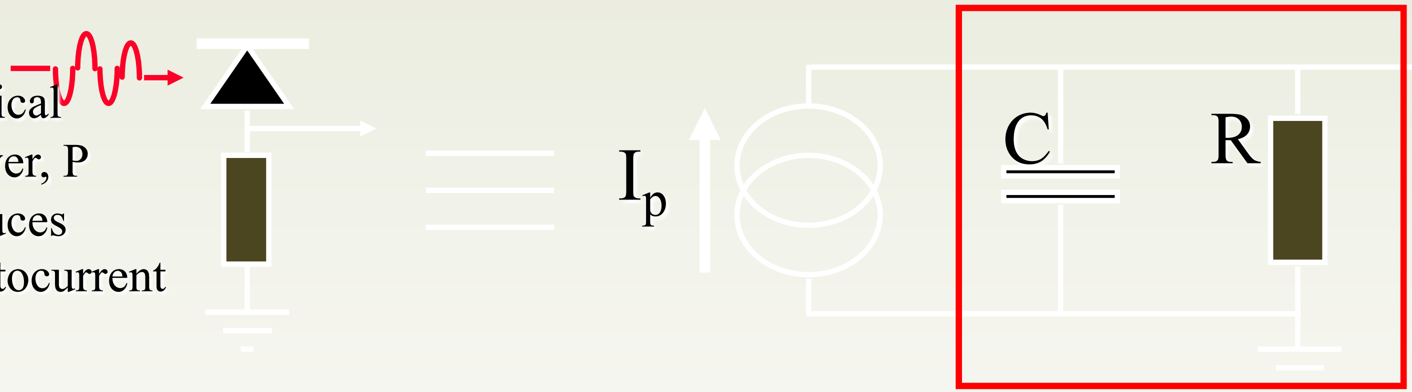
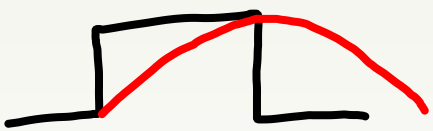


Figure 6. Chip micrograph

Optical power, P induces photocurrent I_p



low pass filter

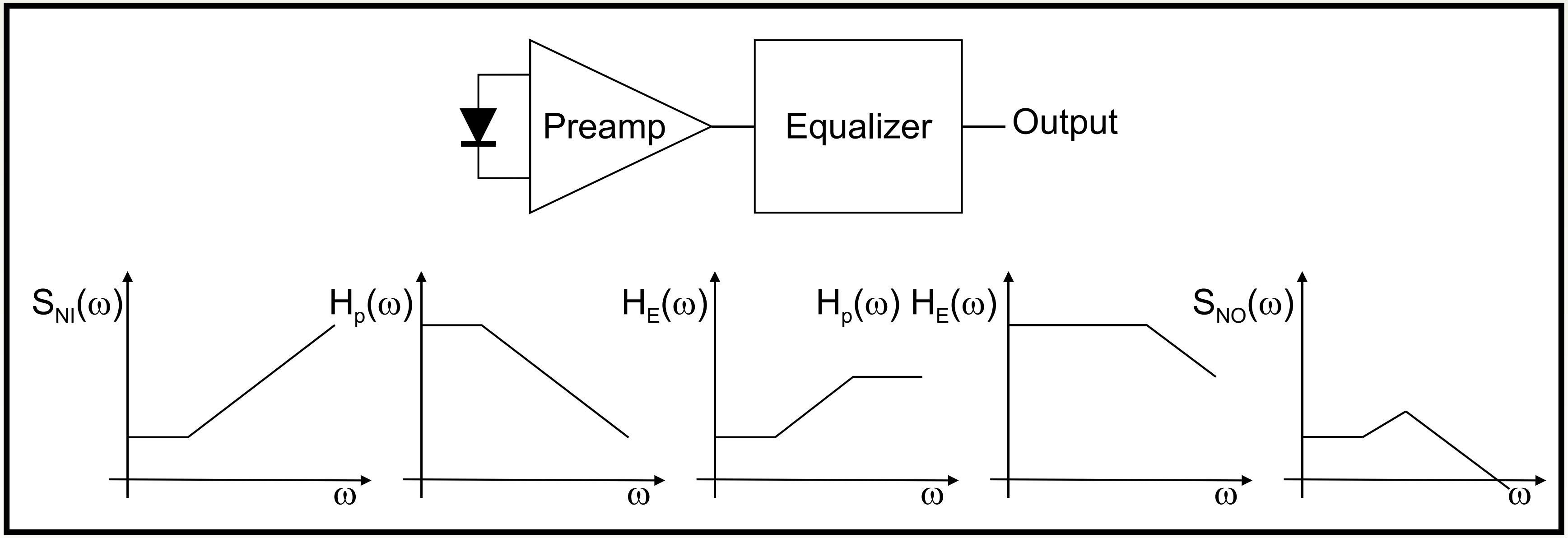


low pass filter will influence the response, RC, which leads to ISI

equalization was used to cope with these phenomenon

Reverse biased photodiode has capacitance C
Terminating resistance is R
Incident light, power P_{opt}, induces photocurrent $I_p = \mathcal{R} P_{opt}$
At high frequencies diode resistance and lead inductance also need to be considered

Equalisation



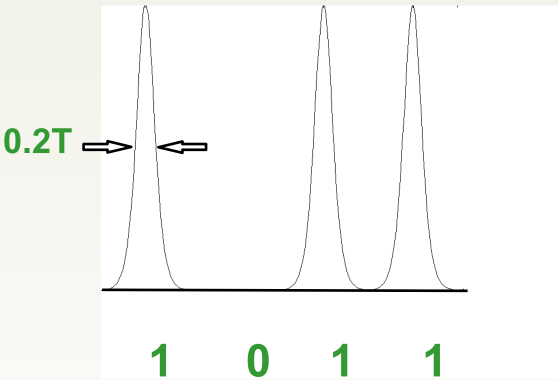
- Equalisation and/or filtering are used to:
  - Extend the bandwidth/compensate for C_d effects
  - Improve error rates by reducing Inter-Symbol-Interference (ISI)
  - Main drawback is……………

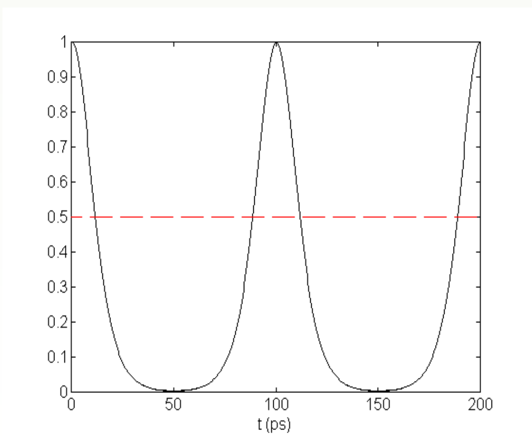
Filtering and Signal shaping

- It is desirable to have a signal with low ISI at the input of the decision device;
- And, with low Jitter characteristics or with tolerance to jitter
- This necessitates designing signals in the time domain.

The filter can be either a separate device or an integrated function within the amplifier

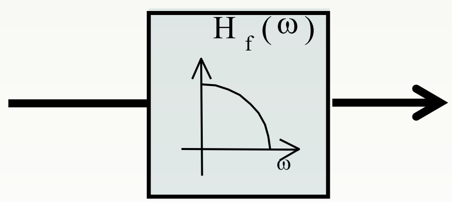
Received signal



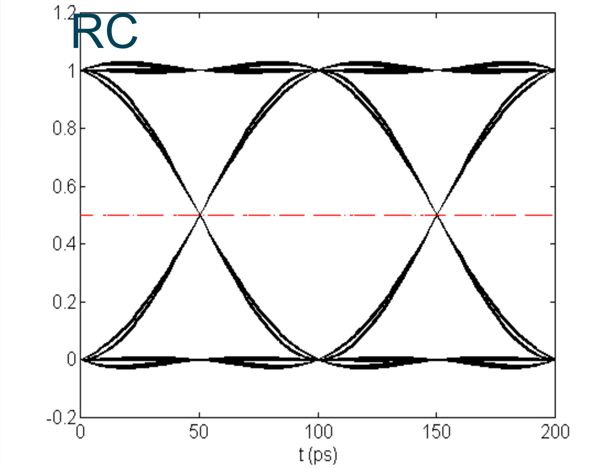


Post-detection filter

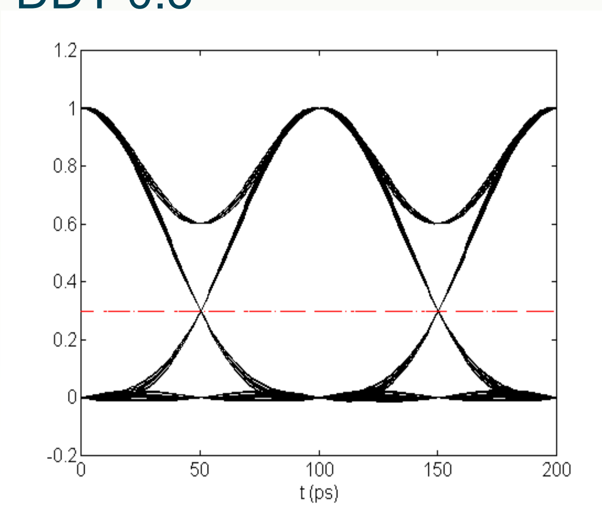
shaping to reduce the ISI



100% RC



DDT 0.3



Receiver post detection pre-amplifiers

- After transmission through a fibre, the received optical signal will result in a small photocurrent (typically in the region of 10^{-6} A). Remembering that the photodetector is effectively a **capacitive current source**, special amplifier circuits have to be designed so that the overall receiver performance is optimised in terms of **Noise, Bandwidth, Stability, Gain and Dynamic range.**
- The amplifiers will have a voltage output that is proportional to the photocurrent input. They are effectively “electronic resistors”. In the literature they are referred to as Trans-Impedance Amplifiers TIAs.
- These amplifiers work with low power signals. They are the most difficult to design and their performance dictates the overall receiver performance.
- Three circuit structures have been widely used for receiver amplifier applications. More on this later.

Optical Receiver Parameters; Gain

- Transimpedance gain is defined as the ratio of the output voltage to the input current (photocurrent).
- In dBΩ it is equal to 20 * Log(Vout/Ip) transiampedance
- For a voltage amplifier preceded by a resistive element, the transimpedance gain is given by the **product of the voltage gain and the input resistance**.
- Occasionally, manufacturers specify gain in V/W (or kV/W). This is effectively a product of the transimpedance gain and the responsivity. This figure is ≤ the transimpedance gain for pin-TIA combination and ≥ the transimpedance gain for APD-TIA receivers.

e.g. 50Ω is 34 dBΩ and 1 kΩ is 60 dBΩ
An amplifier with a voltage gain of 100 (20dB) and an input resistance of 100Ω (40dBΩ) will have a transimpedance gain of 10,000 (60dBΩ). For a pin with a responsivity = 0.8 A/W, the amplifier would also have a gain of 8 kV/W.

Optical Receiver Parameters; Bandwidth

- Normally taken as the 3dB cut-off frequency of the receiver transimpedance gain.
- The bandwidth determines the maximum bit rate at which the receiver can be operated. Usually, the **maximum bit rate ≤ 1.4 f_{3dB}**.
- One of the main factors determining bandwidth of the receiver is the frequency of the input pole, formed by the parallel combination of the photodiode capacitance and the input resistance.
- The response of the preamplifier and the equaliser also determine the bandwidth.
- Some times the bandwidth is “stated” in terms of rise and fall times. A rough estimate is that $BW=0.35/t_r$

dBs - Optical & Electrical - 1

- We often define power ratios in dB by: $10\log_{10}(P_1/P_2)$ dB
- For voltage ratios or current ratios, since P is proportional to V^2, I^2, this gives rise to: $10\log_{10}((V_1/V_2)^2)=20\log_{10}(V_1/V_2)$ for same *R*
- Similarly: $10\log_{10}((I_1/I_2)^2)=20\log_{10}(I_1/I_2)$ for same *R*
- 3 dB corresponds to a power ratio of 2 and a voltage or current ratio of $\sqrt{2}$ (i.e.~1.414)
- -3 dB corresponds to a power ratio of 1/2 and a voltage or current ratio of $1/\sqrt{2}$ (i.e.~0.707)

- In direct optical detection, though, the photocurrent is *proportional* to the received optical power;
- Hence if the received power is halved this is a 3 dB reduction in the optical signal level
- But halving the received optical power (a 3 dB reduction in optical power level) means that the photocurrent will similarly be halved, corresponding to a 6 dB reduction in the electrical signal level
- Care is thus needed when using dB measures in association with direct optical detection

dBs Optical & Electrical - 2

- Consider the 3 dB modulation bandwidth specified for a LED
- Does this refer to the modulation frequency at which the optical or the detected electrical signal will be 3 dB less than the low frequency value?
- Where the optical signal is 3 dB down the electrical signal will be 6 dB down
- The 'optical' 3 dB bandwidth is greater than the 'electrical' 3 dB bandwidth
- A device manufacturer is likely to specify bandwidth in terms of the optical 3 dB frequency (it 'favours' the product)
- The electrical 3 dB frequency may be more relevant for system design and specification purposes

Optical Receiver Parameters; Stability

- Is the ability of the amplifier to operate with no oscillations, and to produce output pulses with minimal peaking/oscillation.
- Unstable operation occurs when there is <u>positive</u> feedback and high gain (think of lasers!!)
- Feedback amplifiers have to be designed very carefully to ensure stable behaviour

Optical Receiver Parameters; Sensitivity

- Is the minimum input optical power that can result in a pre-specified bit error rate (BER).
- The sensitivity improves (i.e. gets lower, resulting in a more sensitive receiver)if the SNR of the receiver is improved. In other words the sensitivity is directly proportional to the input signal level (photodiode responsivity) and is inversely proportional to the rms noise of the receiver.
- There are specific mathematical formulae that relate the receiver BER to the SNR and that can be used to calculate the receiver sensitivity. For example for a BER of 10^{-9} (errors/bit, equivalent to one error per Gbit) the required SNR is approximately 6 (15.6 dB).
- Receiver noise is contributed from two main sources: main noise
  - Thermal noise of *resistive* elements at the input. The lower the resistance (in parallel with the input) the higher the noise.
  - Shot noise of *active* elements of the amplifier (mainly transistors and minor contribution from photodetector). The higher the bias current the higher the noise.

Thermal Noise

- **Thermal noise,** (also known as Johnson noise). This is associated with the random motion of electrons in a conductor and therefore exists in all resistive elements in the receiver. The noise power is directly proportional to absolute temperature. The rms thermal noise current associated with a resistor is given by:
- $\mathbf{I_{noise\_rms(thermal)} = (4.K.T.\Delta \mathit{f} / R)^{1/2}}$ (Amperes)
- where, k is Boltzman's constant = 1.38 * 10^{-23} J/K, K is the absolute temperature in Kelvin, Δf is the bandwidth in Hz and R is the resistor value in Ohms. For low values of resistance at the input of the receiver, this noise component can be significant. For example a 50 Ω resistor at room temperature (300 K) will generate 0.575 μ A of thermal noise in a 1 GHz bandwidth. It is therefore important to increase the value of the resistance at the input of the amplifier if low noise operation is required.

Shot Noise

- This is associated with the discrete nature of current flow in a semiconductor device. It exists in all biased semiconductor devices where electrons have to cross a potential barrier. The rms noise current associated with shot noise is given by:
- $\mathbf{I_{noise\_rms(shot)} = (2.q.I.\,\Delta \mathit{f})^{1/2}}$ (Amperes)
- Where, q is the electronic charge = 1.6 * 10^{-19} C, I is the current passing through the device in Amperes and Δf is the bandwidth in Hz. Again, this noise can be significant if the electronic devices at the input of the amplifier are biased with large currents. Special care must be taken when designing the first stage of the preamplifier receiver.
- I is effectively the sum of two currents; the Photocurrent and the amplifier's bias current. Which of these is dominant?

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To summarise noise…

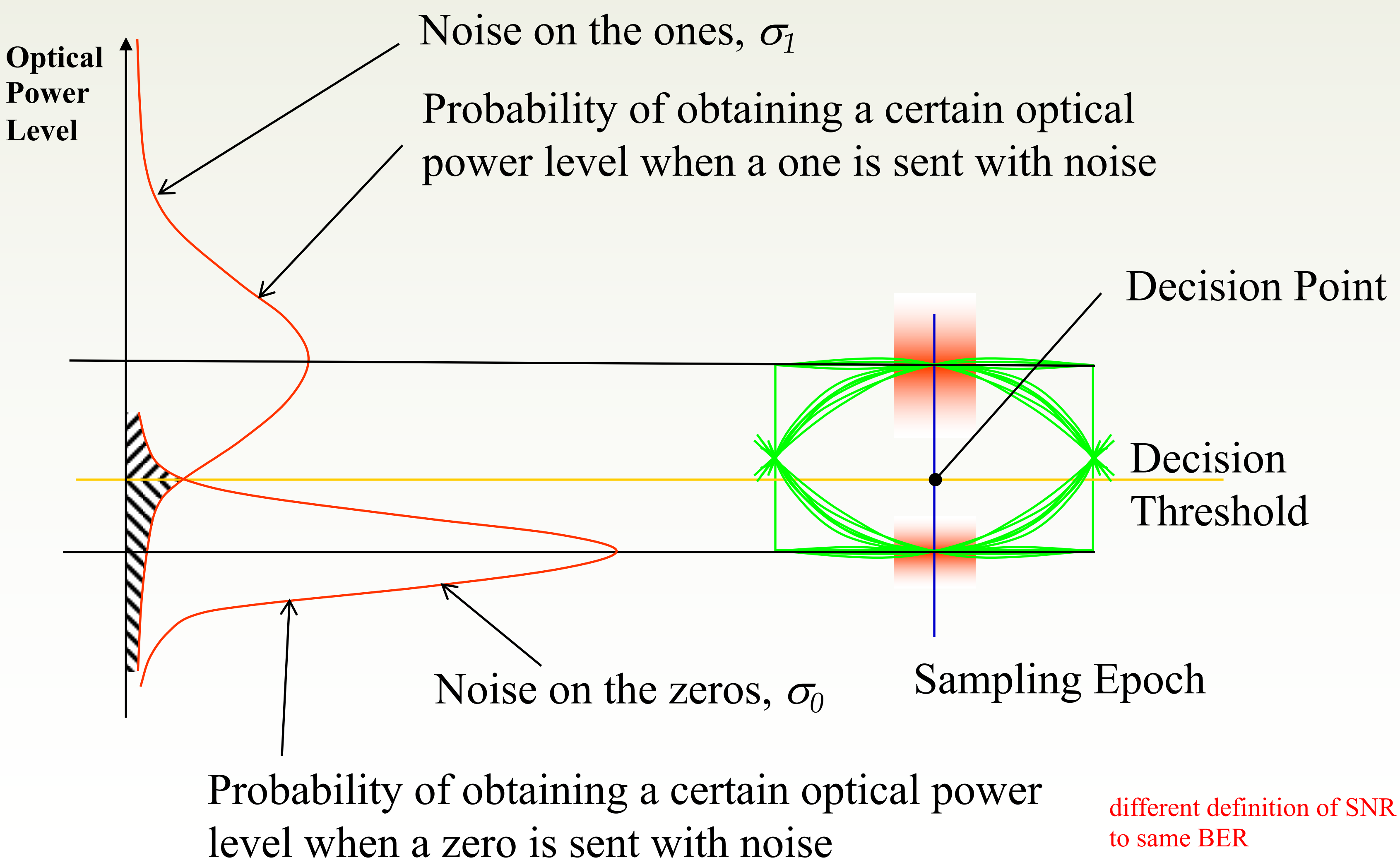
- Quantum noise is inherent to optical communications, but in practice most receivers operate far from the Quantum Limit due to the dominance of receiver noise
- Thermal noise associated with the passive resistance at the input, that is between the input terminal and ground . Mean square current spectral density is $4kT/R$ (in A^2 /Hz) and so this is minimised by using a large value of R
- Amplifier noise, often modelled by equivalent noise current and noise voltage sources at the input
- Low impedance receivers are dominated by thermal noise
- High- and trans-impedance receivers are dominated by input voltage noise and the output noise spectral density then has strong f^2 dependence

$$\sigma^2 = \sigma_s^2 + \sigma_T^2 = 2q\left(I_{photo} + I_{amp}\right)B + \frac{4kT\,B}{R_L}.F$$

The total noise is the sum of contributions from all noise sources.
It is normally referred to the input and expressed as an rms figure

Signal Dependent Noise

the noise on 1s is larger than 0s



different definition of SNR will lead to same BER

Optical Receiver Parameters; Dynamic range

when the SNR reaches the value , BER will not be less, and even worse

- Is the difference (in dBs) between the maximum signal power allowed at the receiver input (so as not to cause saturation and signal distortion) and the minimum signal acceptable at the input (sensitivity)
- Some times manufacturers specify “input overload “ parameter. The dynamic range can be easily estimated from that if the sensitivity is known
- Alternatively (or additionally) manufacturers may specify a “maximum output voltage”. Again, the dynamic range may be estimated.

High impedance amplifier (HZ)

$Br \approx 1/(2 * \pi * CR) > Bs$

•A large termination resistance R is employed, which introduces less circuit noise but severe CR band-limiting occurs.

•This results in signal integration and base line wander, limited dynamic range.

•A differentiator following the receiver corrects for front-end integration with a net overall noise advantage.

Low impedance amplifier (LZ)

- The photodiode is terminated in a resistance which is sufficiently low that the capacitance of the photodiode and receiver input circuitry do not unduly limit the bandwidth the receiver.

- Receiver bandwidth B_r relative to the required system bandwidth B_s is :

$$Br \approx 1/(2^* \pi^* CR) > Bs$$

Trans-impedance amplifier (TZ)

–The passive resistance is large, providing low noise.

–Negative feedback ensures that the effective input resistance is low, ensuring $Br > Bs$

$$Br \approx 1/(2 * \pi * CR) < Bs$$

•Care must be taken about stability

A typical circuit

FET based Transimpedance amplifier

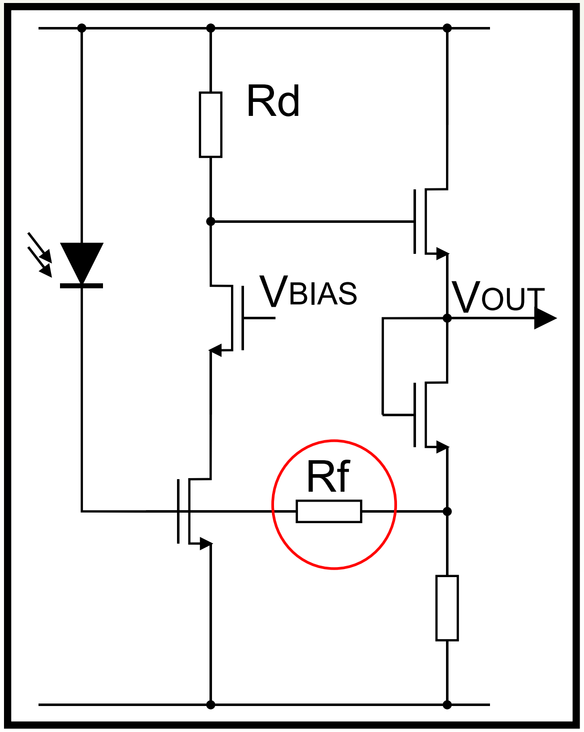
Notice, no current flow in the first transistor input

Rf stabilises the gain (Gain ~ Rf)

Increases the bandwidth

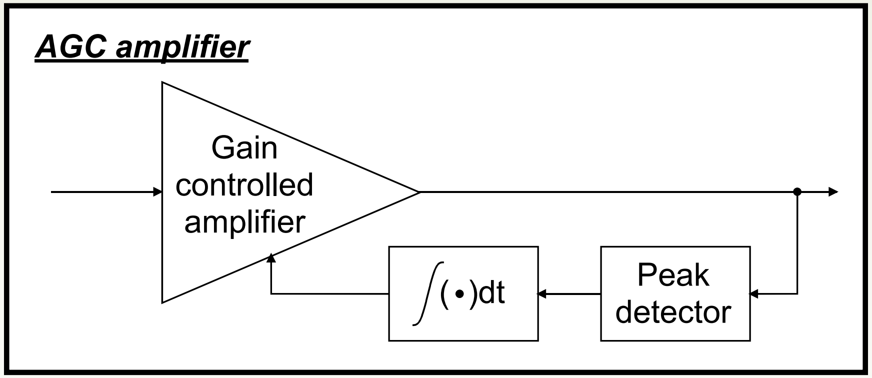
but increases the noise!!

$$S(f) = \frac{4kT}{R_f} + 4kT \cdot \left[\Gamma g_m + \frac{1}{R_d} \right] \cdot \left(\frac{\omega C_T}{g_m} \right)^2$$

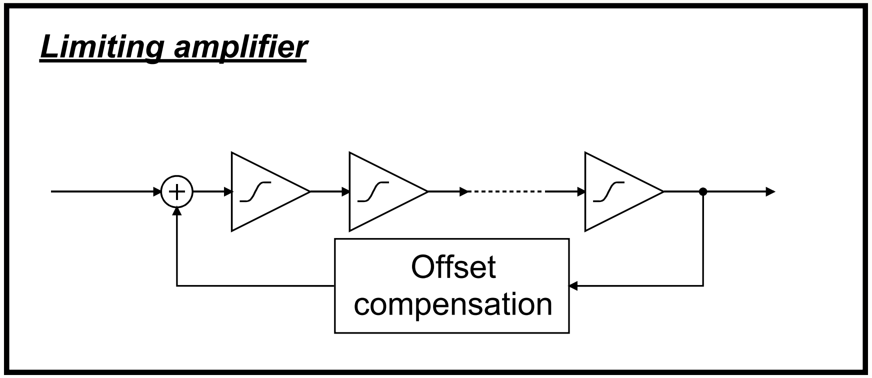


Limiting and AGC amplifiers:

- Commonly used to amplify the TIA signal to full logic levels
- AGC amplifiers adapt the gain to the signal level:
  - For large input signals, avoids overdriving the amplifying stages or the following circuit
  - For small input signals, the gain is maximized reducing the amplifier noise contribution

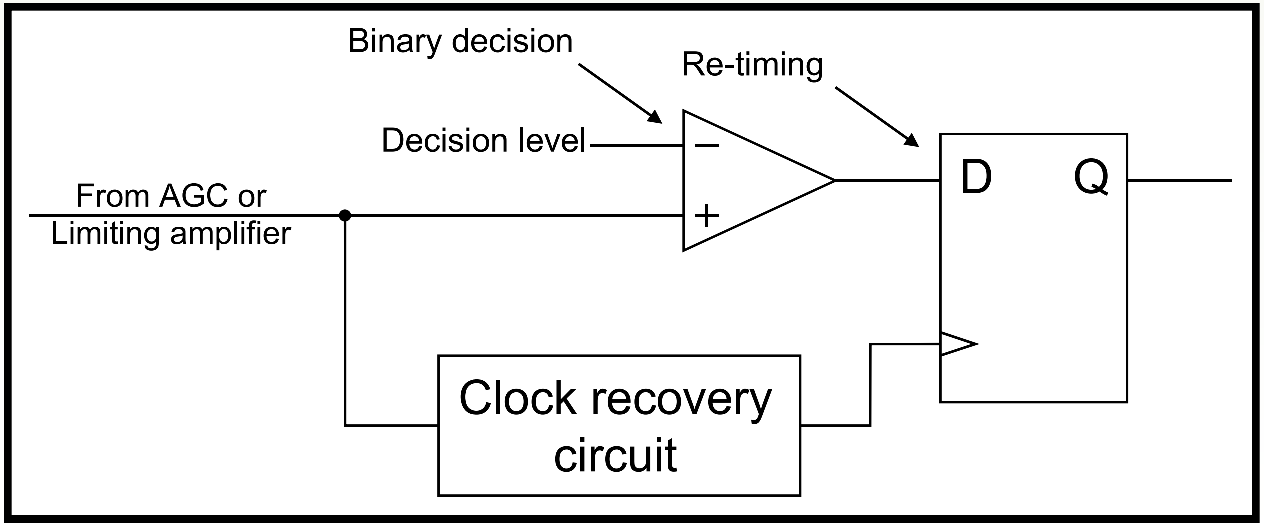


- Limiting Amplifiers:
  - Use the amplifier intrinsic non-linearity to avoid overdrive
  - Noise is minimized by always using maximum gain
  - Cascades of low gain stages are often used to achieve high gain-bandwidth products
- Both type of amplifiers tend to be fully differential to maximize noise rejection
- The limiting amplifier can be replaced by a decision circuit (Hard limiter).



Clock and Data Recovery CDR

- These functions are essential in digital receivers to ensure signal regeneration with correct levels and timing

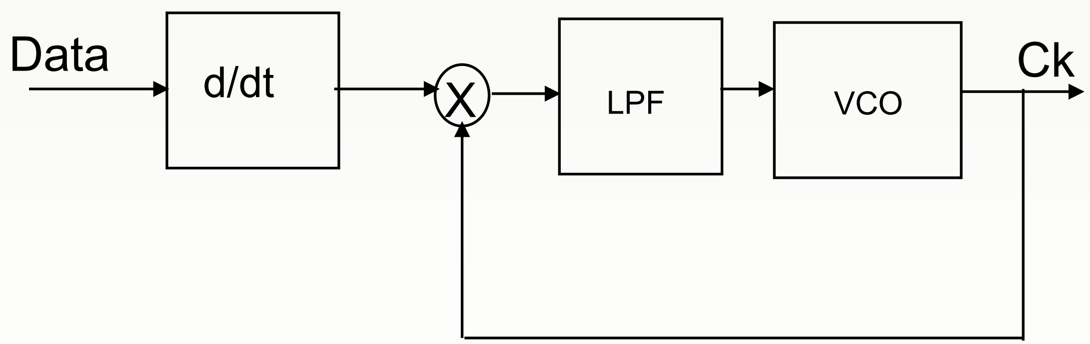


Clock recovery

- Random NRZ binary signals do NOT have a spectral component at the signal/bit rate (unless appropriate coding is used)
- The CRC function is to "create" such a component
- This requires non-linear processing, effectively signal differentiation (edge detection) and then rectification to create a component at 2xbit rate
- A phase locked loop satisfies this
- For NRZ data, a good narrow band filter will suffice!!

Phase locked loop for clock recovery

- The VCO is controlled by a slow varying error voltage that corresponds to the difference in frequencies between the two multiplier inputs
- Effectively, the PLL implements a narrow band pass filter with the ability to track the frequency with minimum jitter addition.



Clock recovery can be implemented in the optical domain using a variety of techniques, OPLL, ring oscillators based on EAMs Fibre ring lasers…etc

A recent example@40 Gbit/s

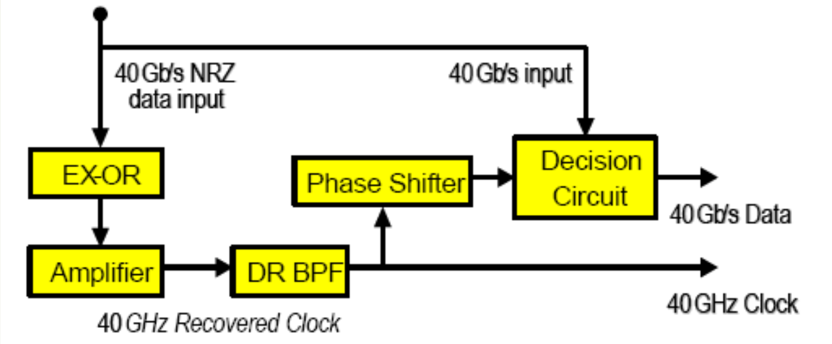


Fig.1 Block diagram of an open loop type CDR

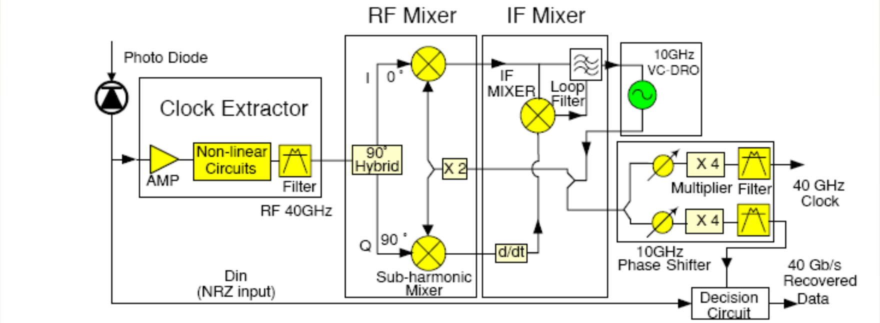


Fig. 2 Block diagram of the proposed phase-locked loop CDR

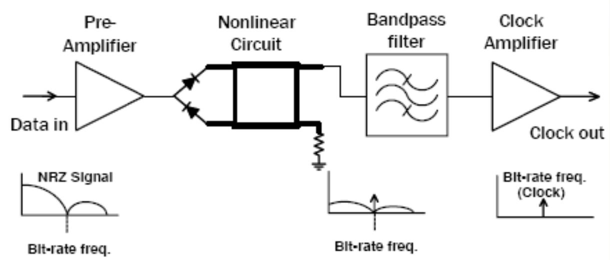
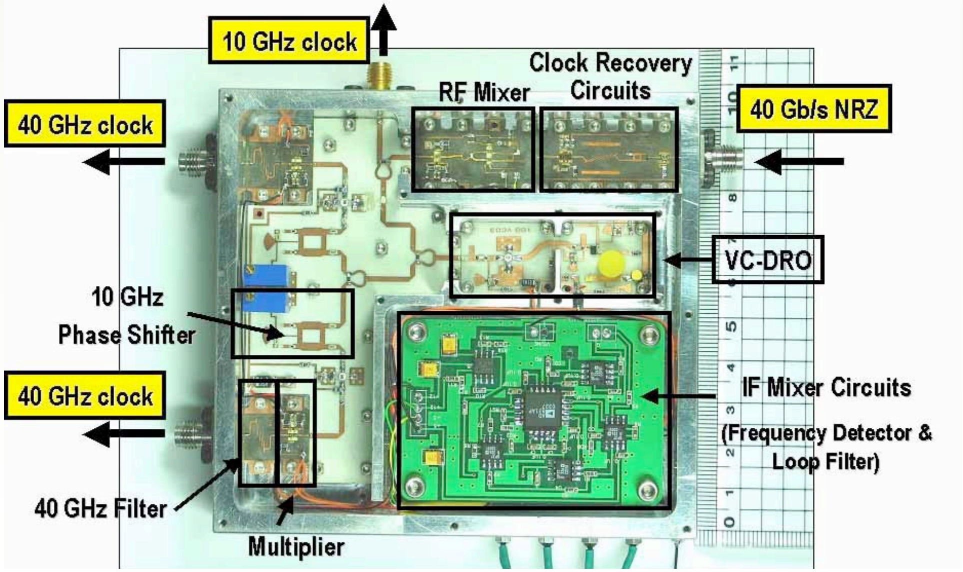


Fig. 3 Block diagram of the clock extractor circuit



Implementation of a phase-locked loop clock recovery module for 40 Gb/s optical receivers

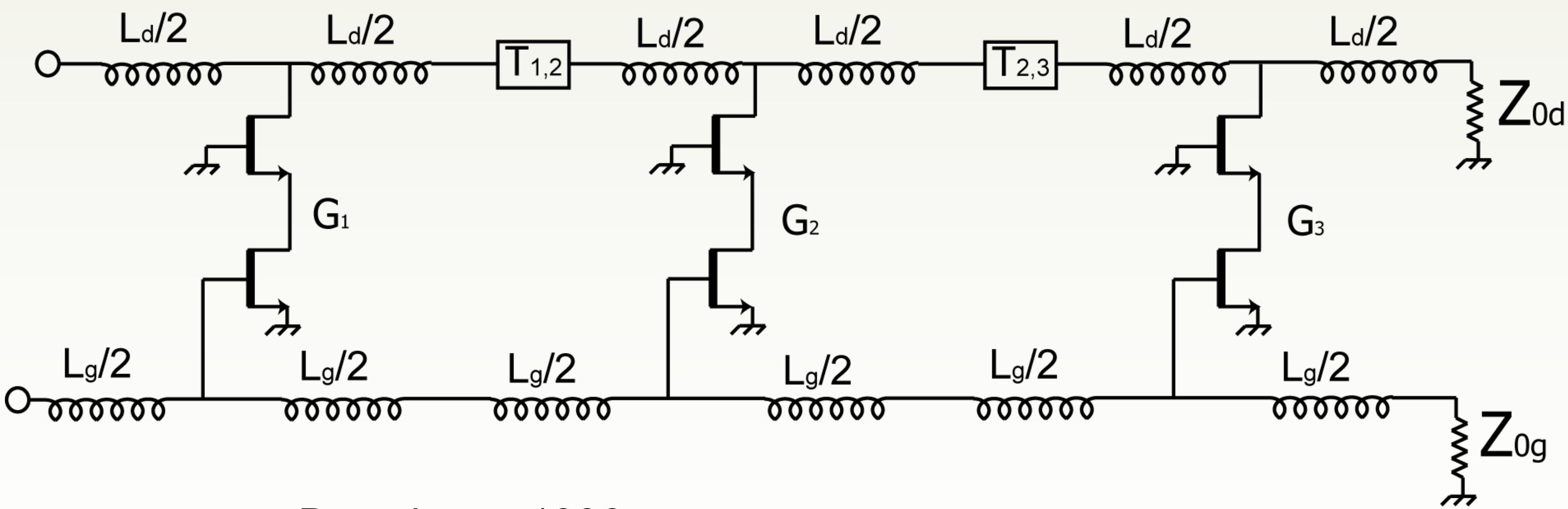
Chan Ho Park; Dong Sik Woo; Tae Gyu Kim; Sang Kyu Lim; Kang Wook Kim

MTT-S 2005

Implementation Technologies

- For low speed, up to 10s MHz, either discrete components or even opamps can be used
- For high speed implementation several technologies (IC processes) are available;
  - GaAs
  - InP (with optical components)
  - Si (CMOS and BiCMOS sub-micron processes)

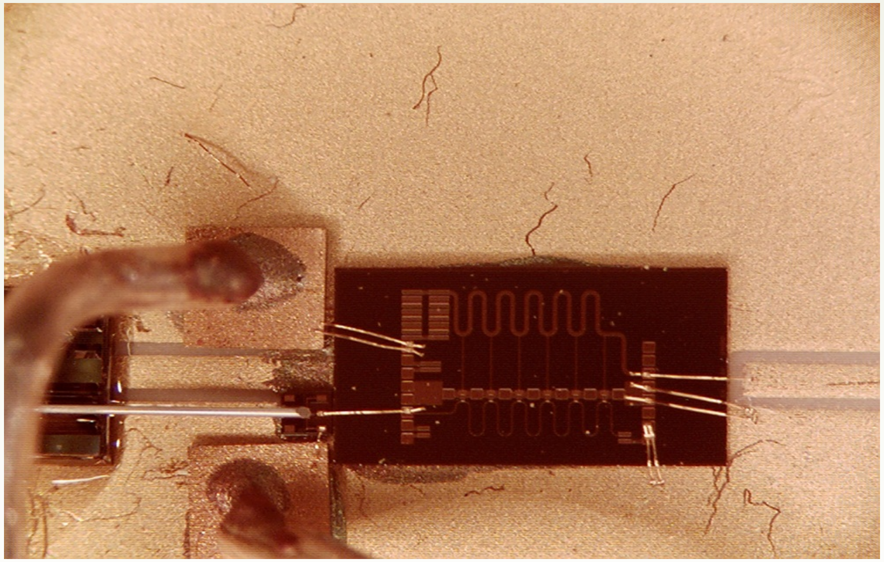
The Distributed- Amplifier Topology
Used for very high speed applications, > 10 Gbit/s



Based on a 1936 patent…

MMIC optical Receiver - I

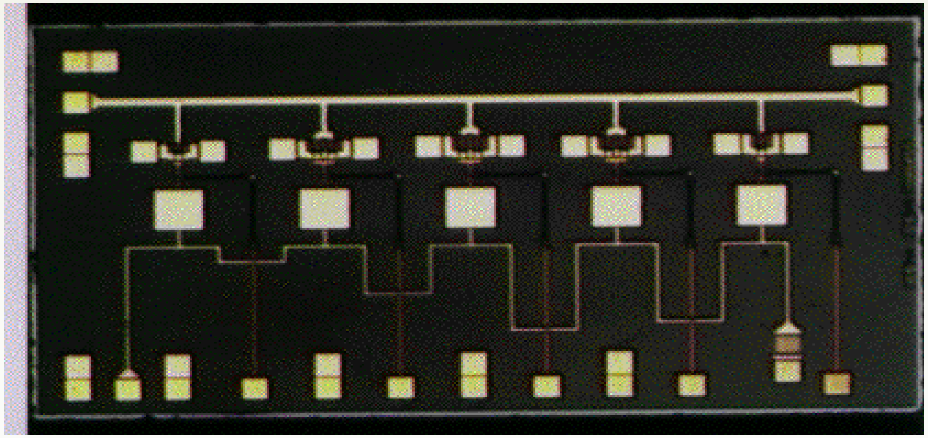
- 10/ 20 Gbit/s
- Distributed Amplifier
- DC - 17 GHz
- MESFET technology



A. Borjak, P. Monteiro, I. Darwazeh and J. O'Reilly
"Multigigabit Distributed Amplifiers for Signal Shaping Applications",
Electronics Letters 32 (4), pp. 355-356, 15th Feb. 1996.

MMICs for optical Receiver - IIa

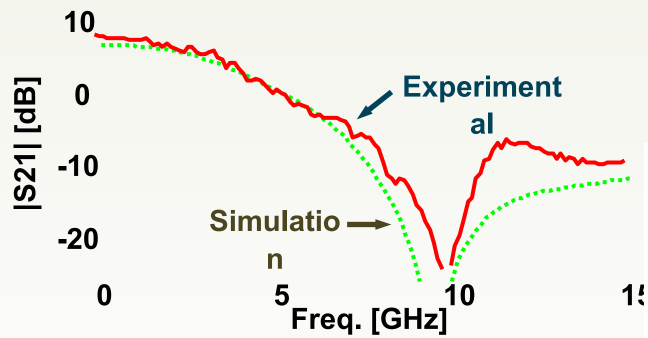
- 10 Gbit/s transversal filter
- Use in Soliton systems
- Variable signal shaping
- DC adjustable filtering

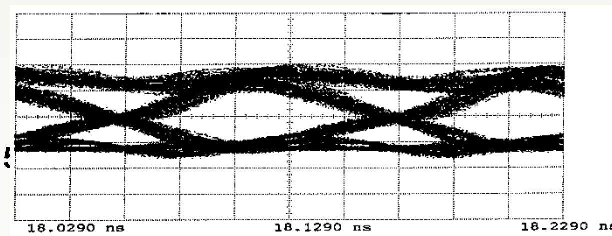


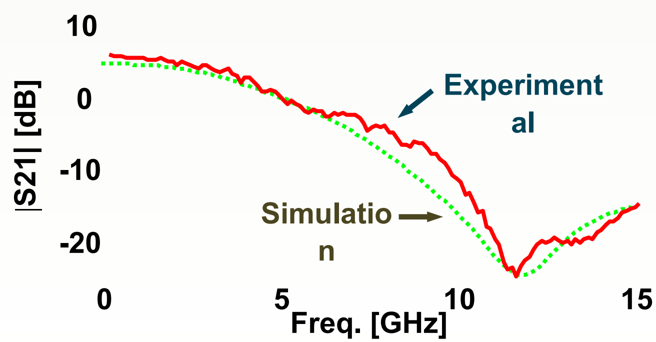
P. Monteiro, A. Borjak, J da Rocha, J. O'Reilly and I. Darwazeh, **"Adjustable Post-Detection Filter for Optically Amplified Soliton Systems"**, IEICE Transactions on Electronics, Vol. E85-C, pp. 511-518, March 2002.

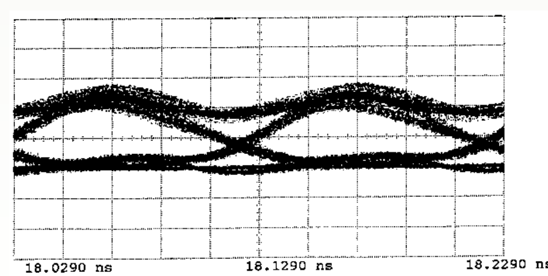
MMICs for optical Receiver - IIb

Experimental Frequency response and eye diagrams

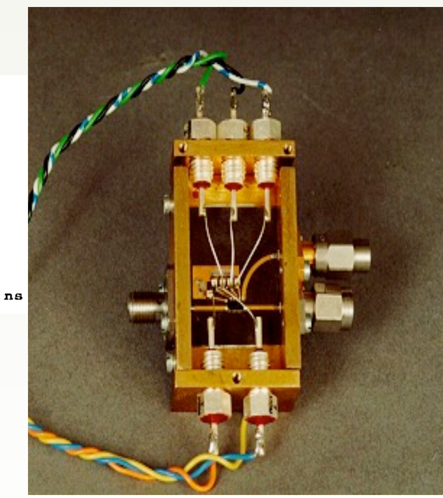






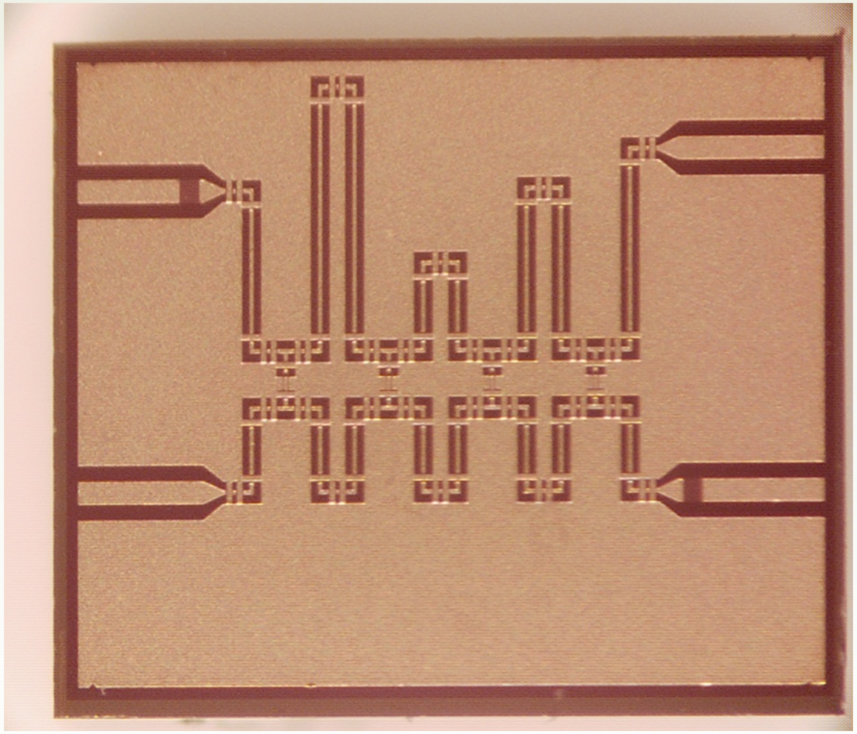


ASSEMBLED PROTOTYPE



MMICs for optical Receiver - III

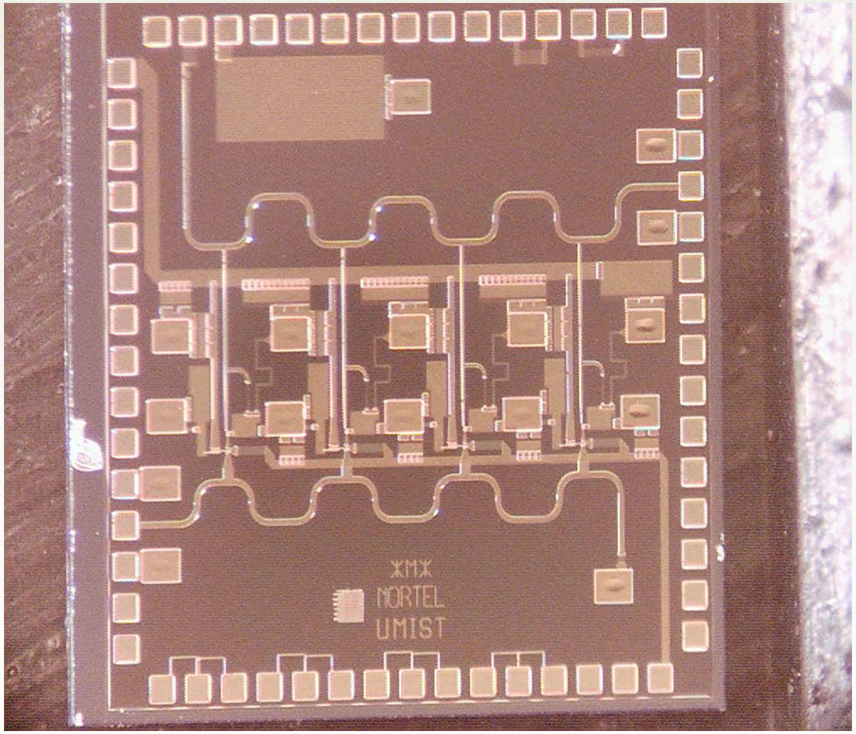
- 40 Gbit/s Optical receiver
- Distributed amplifier topology
- HEMT technology
- Transversal filter approach
- 100% RC shaping



A Borjak, P. Monteiro, J. O'Reilly and I Darwazeh,
"High Speed Distributed Amplifier Based Transversal Filter Topology for Optical Communication System",
IEEE Transactions on Microwave Theory and Techniques, Vol. 45, No. 8, pp.1453-1458, August 1997.

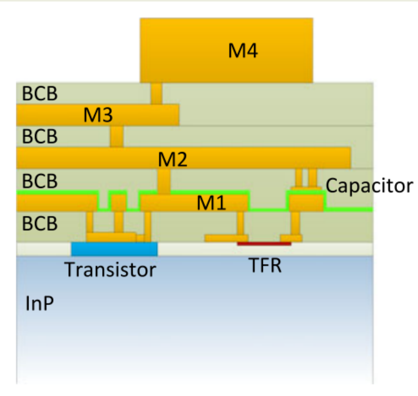
MMICs for optical Receiver - IV

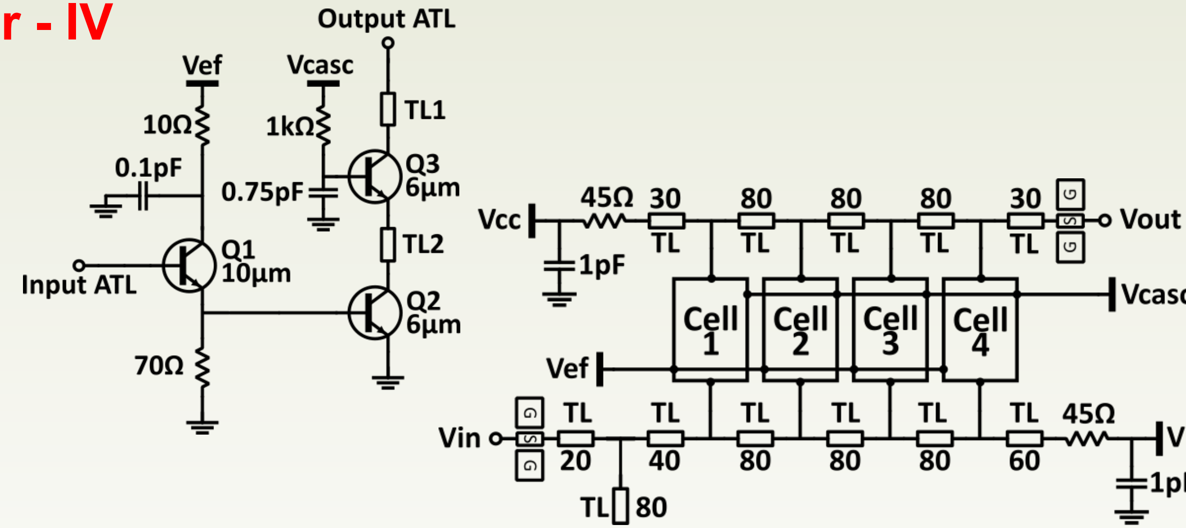
- 30 Gbit/s receiver
- Ultra wide band
- f_{3dB}-high = 23 GHz
- f_{3dB}-low = 100 kHz
- HBT technology

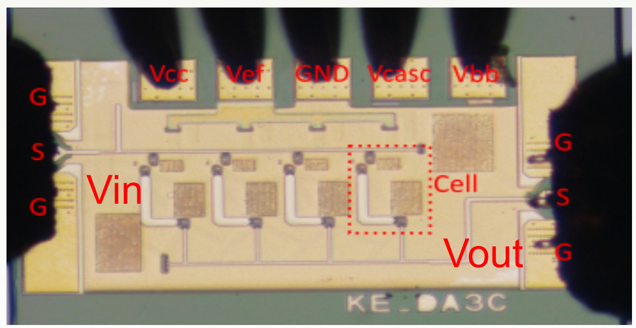


Iqbal and I. Darwazeh, **"23 GHz Baseband HBT Distributed Amplifier for Optical Communication Systems"**, Proceedings of 28th European Microwave Conference (EuMC-98), Vol. 1, pp. 6-11, Amsterdam – Holland, Oct. 1998

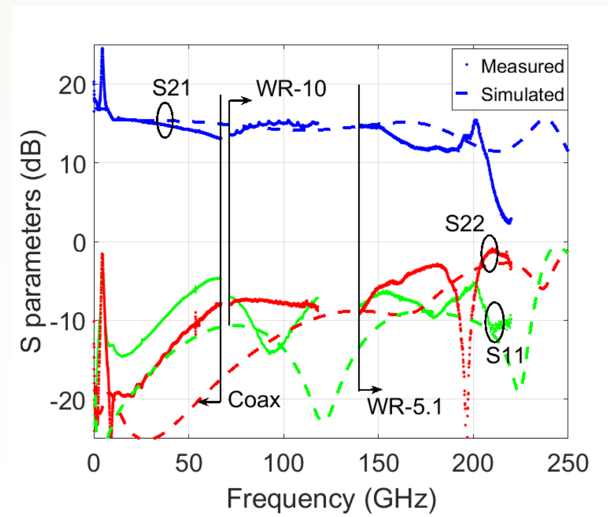
MMICs for optical Receiver - IV







720 μm x 400 μm



- InP 250nm DHBT by Teledyne 4 metal layers
- MIM capacitors
- Thin film resistors
- f_t/f_{max} : 350 GHz / 600 GHz
- 3.5 dB average gain with 2dB gain ripple
- 207 GHz bandwidth

Stavros Giannakopoulos[1], Klas Eriksson[2], Izzat Darwazeh[3], Zhongxia Simon He[1], Herbert Zirath[1]
“Ultra–Broadband Common Collector-Cascode 4-cell Distributed Amplifier in 250 nm InP HBT Technology with over 200 GHz Bandwidth ”, Proceedings of 28th European Microwave Conference (EuMC-98), Vol. 1, pp. Nuremburg– Germany, Oct. 2017

Future trends

- Full integration/OEICS
- Digital signal processing in the receiver
- Adaptive compensation and equalization
- Getting closer to the quantum limit