Optical communications and data networks (EENGM2001)

Siddarth K Joshi

Approx 25 hour unit given by Siddarth K Joshi (sk.joshi@bristol.ac.uk)

10 Credit point module = 100+ hours of study:

12 hours of synchronous lectures (in person):

13 hours of Asynchronous (virtual lectures):

Minimum of 75 hours of self study.

Tuesdays: 15:00 to 15:30 Lectures.

15:30 to 16:00 Problems.

Mondays: 10:00 am to 11:00 am : Introduce basic concepts

Tuesdays: 15:00 to 15:30 : Applications of these concepts

Wednesday to Friday: Asynchronous lectures

Lectures in Balckboard. Filename formats Week#_Sequence#_Sync/async_Topic

Must complete Async lectures for each week before next class on the following Monday.

Evaluation:

Just one exam at end of semester (date and details to be announced)

Intended learning outcomes

1) Describe the key issues and building blocks in modern optical communications systems;
2) Describe optical transmitters and receivers, or transceivers, methods of modulating light wave carriers with digital data, and methods of demodulation.
3) Describe the main factors limiting the data transmission speed and distance in optical fibre communication systems;
4) Describe methods of overcoming above limitations to achieve higher data speed, longer transmission distances, and larger overall transmission capacities.
5) Describe and specify an optical communications system.
6) Outline future directions of technological developments in optical fibre communications.

	Reference	Comments
[1]	Agrawal, G. P. (2010) Fiber-optic communication systems. 4th edn. Hoboken, N.J.: Wiley.	The canonical resource
[2]	Cvijetic, M. (2004) Optical transmission systems engineering. Boston: Artech House (Artech House optoelectronics library).	Systems engineering
[3]	Rajiv Ramaswami & Kumar N. Sivarajan, ‘Optical Networks: A Practical Perspective’ 2nd Ed., Morgan Kaufmann, ISBN 1-55860-655-6.	Problems
[4]	Sibley, M. J. N. (2020) Optical communications : components and systems. 3rd edn. Cham: Springer.	Problems
[5]	I. Kaminow and T. Li, ‘Optical Fibre Communications, Ed. IV, B (systems and impairments)	Advanced Reading

Lesson plan:

See Blackboard.

Components $\Rightarrow$ Systems

Introduction

Open Systems Interconnection model (OSI model):

7 Layers

ISO/IEC 7498 a.k.a ITU-T Recommendation X.200

Layer			Protocol data unit (PDU)	Function[21]
Host layers	7	Application	Data	High-level APIs, including resource sharing, remote file access
	6	Presentation		Translation of data between a networking service and an application; including character encoding, data compression and encryption/decryption
	5	Session		Managing communication sessions, i.e., continuous exchange of information in the form of multiple back-and-forth transmissions between two nodes
	4	Transport	Segment, Datagram	Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing
Media layers	3	Network	Packet	Structuring and managing a multi-node network, including addressing, routing and traffic control
	2	Data link	Frame	Reliable transmission of data frames between two nodes connected by a physical layer
	1	Physical	Bit, Symbol	Transmission and reception of raw bit streams over a physical medium

Our main focus

Physical layer

Functions:

- **Bit synchronization**: The physical layer provides the synchronization of the bits by providing a clock. This clock controls both sender and receiver
- **Bit rate control**: The Physical layer also defines the transmission rate i.e. the number of bits sent per second.
- **Physical topologies**: Physical layer specifies the way in which the different, devices/nodes are arranged in a network e.g. bus, star, or mesh topology.
- **Transmission mode**: Physical layer also defines the way in which the data flows between the two connected devices.

Physical layer

Parts:

Transmitter
- Laser/LED
- Modulator

Medium
- Optical Fibre
- Free space

Receiver
- Photodiodes
- Homo/heterodyne detectors

Topics of interest:

Encoding data	Losses	Noise
Modulation Schemes	Propagation errors	De-modulation
Security of information	Amplifiers	Power budget
Transmitter properties	Resource optimisation	

The basics

All data is binary: i.e. 0s and 1s

Which layer translates between binary and human readable form?

Bit: Each 0 or 1 is a bit abbreviation b

Byte: 8 bits = 1 byte abbreviation B

Kilobyte: 1024 bytes abbreviation KB

Kilobit: 10^3 bits abbreviation Kb

Megabyte: 1024 KB abbreviation MB

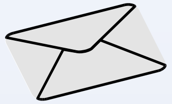
Megabit: 10^6 bits abbreviation Mb

Kilo → Mega → Giga → Tera → Peta → Exa → Zetta

Security

- Prevent others from reading your data → Encryption
- Ensure that you communicate with the right person/device → Authentication
- Make sure your message actually reaches → Reliability

Basic encryption



Alice encrypts

Bob decrypts.

Eve should not know anything.

Basic encryption

Encryption needs a key (password)

The XOR operation

Message

Key

Encrypted

Inputs		Outputs
X	Y	Z
0	0	0
0	1	1
1	0	1
1	1	0

11100010

01111011

10011001

Random key

10011001

Eve gets randomness

1001 1001

XOR 0111 1011 Key

1110 0010 Message

Security

- The problem is now distributing the key
  - Use mathematical problems like Prime factorisation
- Which layers does encryption happen?
  - Hint TLS and SSL are the most commonly used protocols.

Security

- The problem is now distributing the key
  - Use mathematical problems like Prime factorisation
- Which layers does encryption happen?
  - Hint TLS and SSL are the most commonly used protocols.
  - Applications typically treat TLS as if it were running in the transport layer
  - But requires handshake so it also needs the presentation layer
- SSL Deprecated in 2015
- TLS currently ver 1.3
- Algorithm based security protocols have limited lifetime

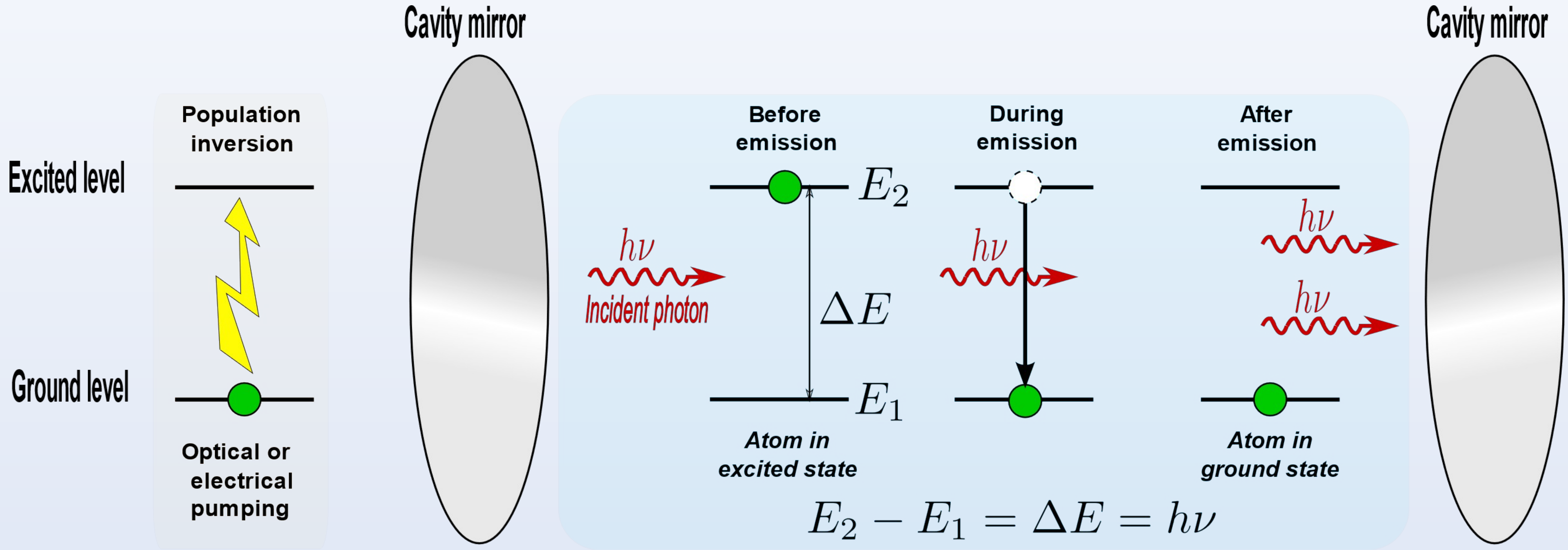
Handshake: a signal between devices for coordination. Typically used to enquire and confirm connection/signal status

Compression

- Data on networks is almost always compressed.
- Compression: Identify patterns in data and save the patterns rather than the raw data to reduce number of bits.

We focus on the physical layer and thus do not care about the meaning of the binary data.

Recap: What is a laser?



Balance between Spontaneous emission, absorption & induced emission ➡ Phase coherent output.

Wavelength linewidth depends on cavity, gain medium & output power

More in Week13 Lecture003_Async

Wavelength Vs Frequency

Frequency f [Units Hz] {E.g. THz, GHz, MHz, KHz, mHz, etc}

Wavelength (lambda) λ [Units m] {E.g. nm, micron or μm or um}a

Speed of light in vacuum c

c = 299 792 458 m/s

We will always use the approximate value of c = 3E8 ($3*10^8$)

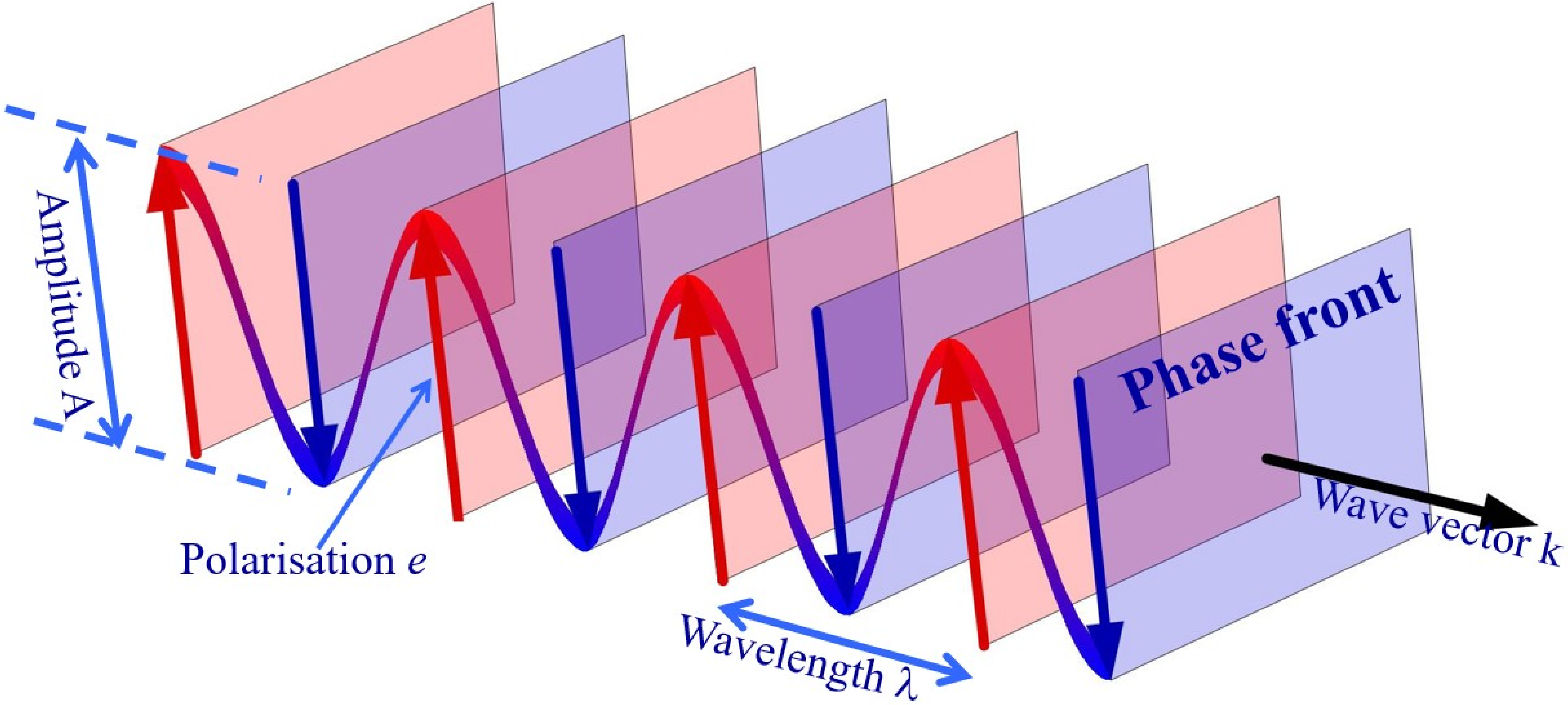
Conversion between f and λ is an ILO

$$f = \frac{c}{\lambda}$$

What is the frequency of 1550.12 nm in THz?

Light as a wave

$$E(t) = \hat{e} A exp\{j[2\pi \upsilon t - kz + \phi]\}$$

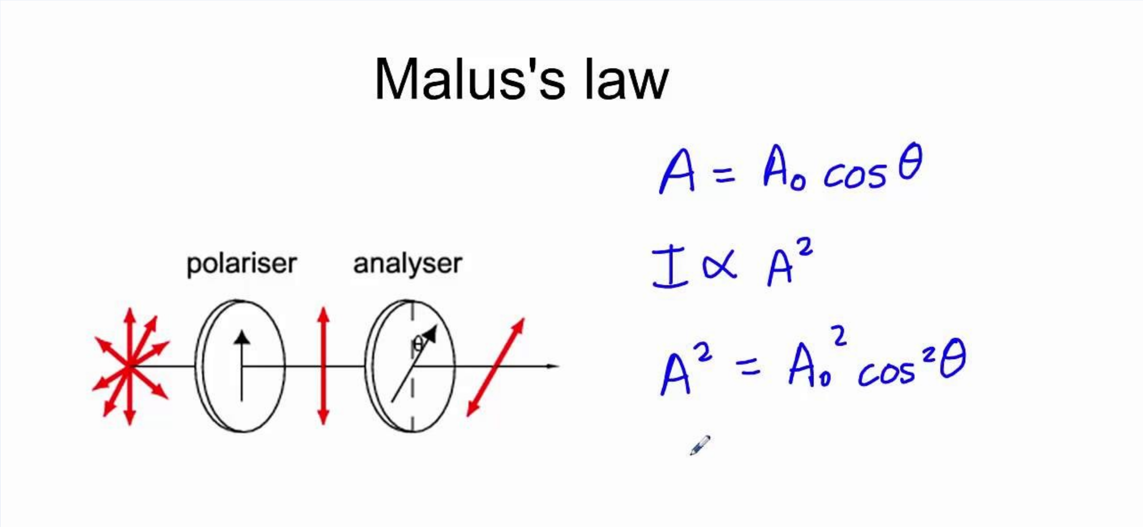


Polarization
Amplitude A
frequency ν
wave vector k
phase ϕ
Power of light $I \propto A^2$

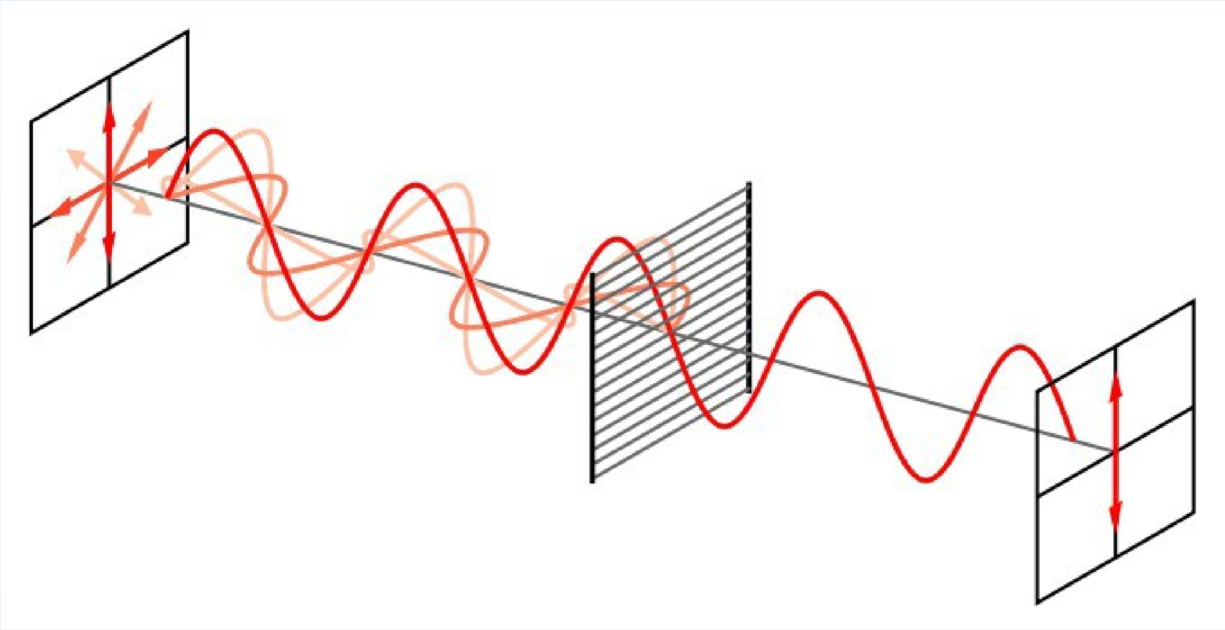
Polarisation

- Direction of oscillation of Electric field.
- When passing through a polarizer:

Malus’s Law

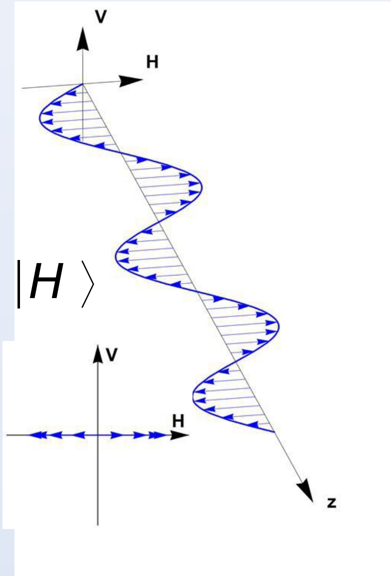


Another ILO

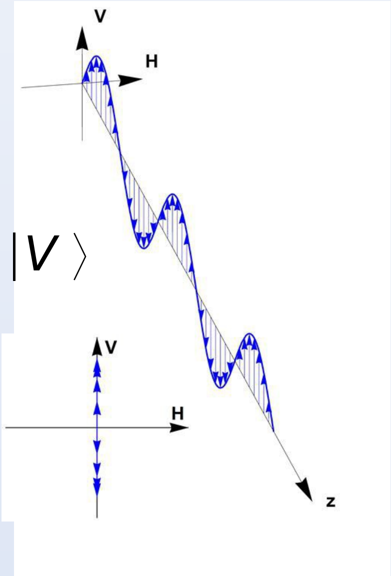


Polarisation

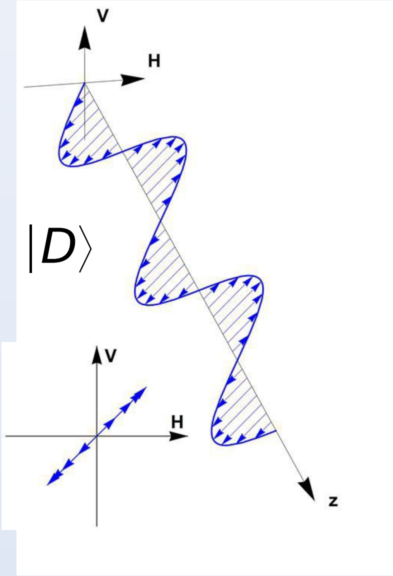
- Direction of oscillation of Electric field.
- When passing through a polarizer: ⇒ Malus's Law
- Can oscillate in any plane



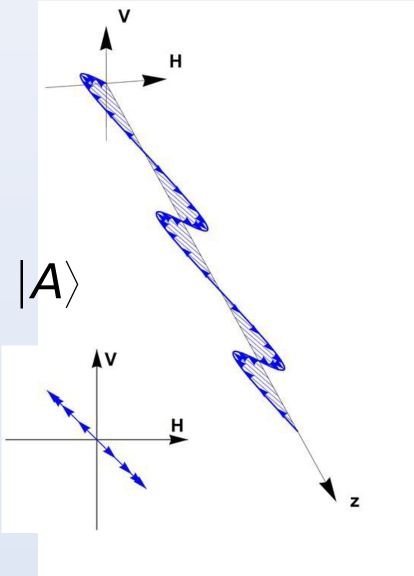
Horizontal



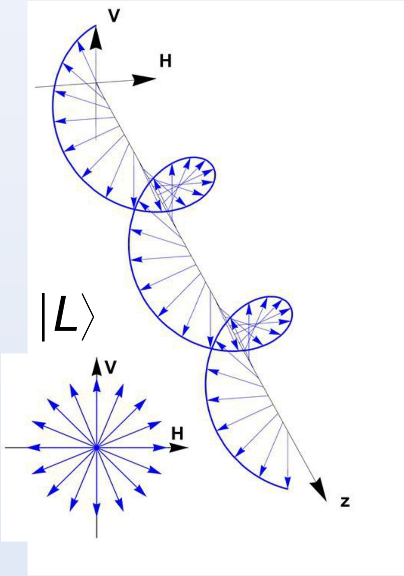
Vertical

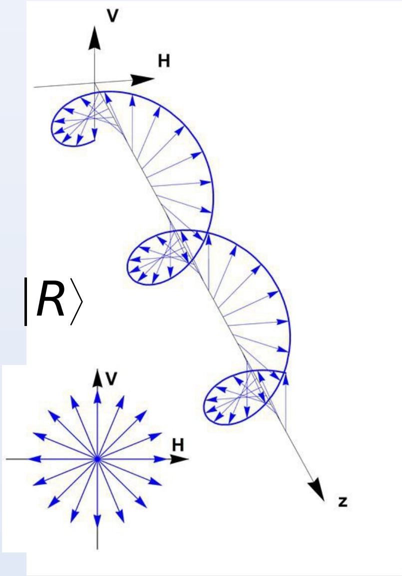


Diagonal



Anti-diagonal





Left and Right handed
Circularly polarized

Wave number/vector

Wave vector (wave number) in vacuum

$$k = \frac{2\pi}{\lambda}$$

Wave vector (wave number) in a medium with refractive index n

$$k = \frac{2\pi}{\lambda} n$$

k is the number of 2π phase shifts per unit propagation distance

Wavenumber k is not an independent parameter

Wave vector in a homogeneous medium with refractive index n

$$\upsilon = \frac{c}{2\pi n} k$$

Wave vector in a waveguide (or other media with boundary conditions)

$$k = D(v)$$

Dispersion relation

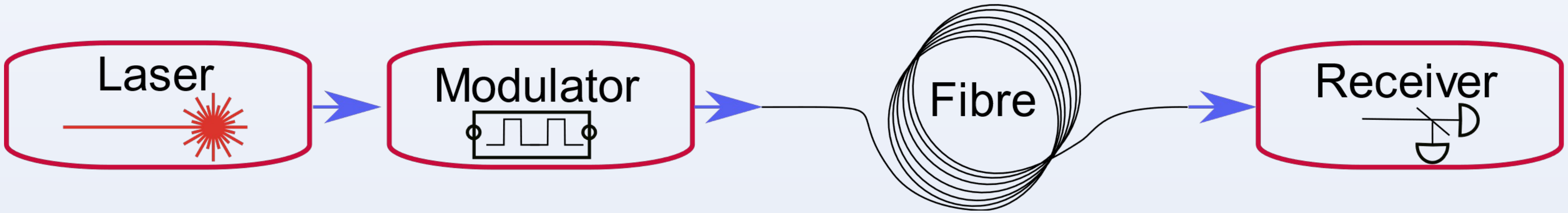
More about dispersion in Week 16

Modulation

ILOs

- Understand various modulation formats used in optical communications
- Learn various methods and devices for realising optical modulation

Modulation



Types:

Sub-Types:

- Amplitude → On Off Keying (OOK), Amplitude Shift Keying (ASK)
- Phase → Phase Shift Keying (PSK)

Both can be upgraded to Quadrature (Q) : QPSK, QAM

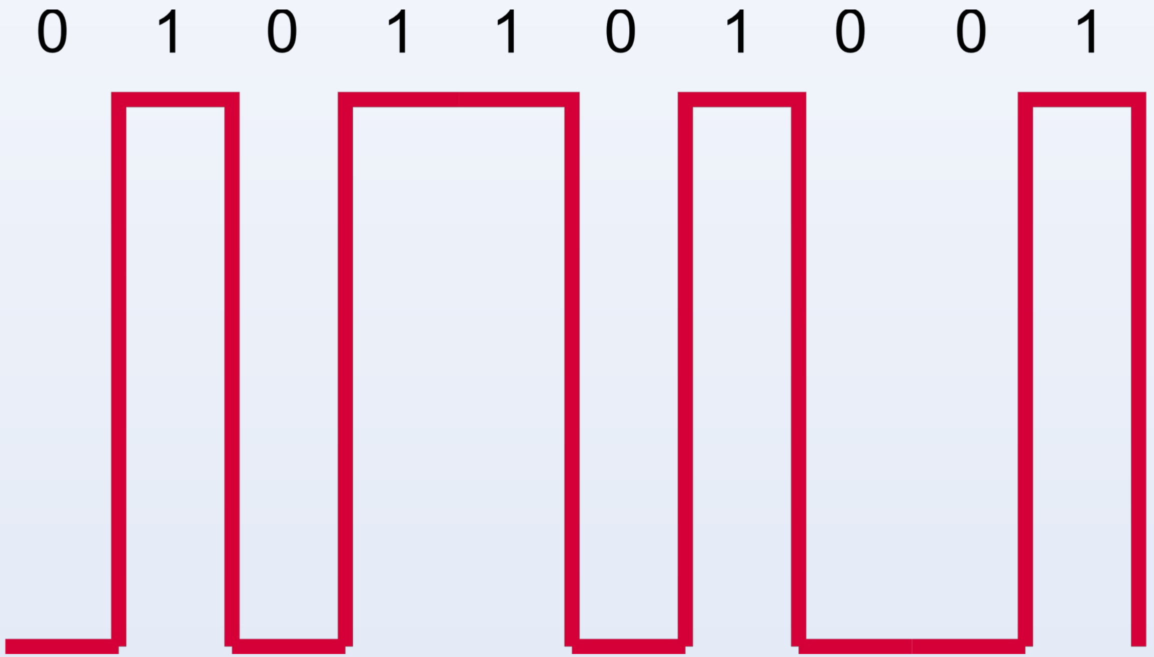
Modulation

$$\mathrm{E}(t) = \hat{e}A(t)exp\{j[2\pi\upsilon t - kz + \phi(t)]\}$$

:

OOK

- ✓ Very simple
- ✓ Amplitude modulation
- ✓ Cheap transmitter and receiver



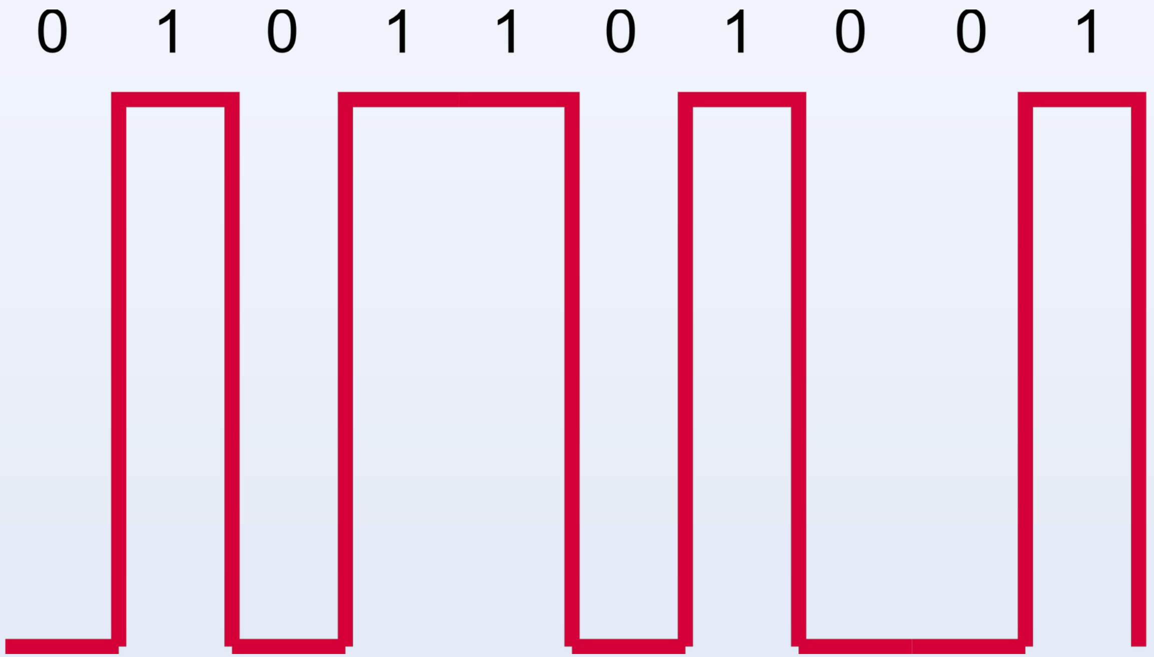
- Requires clock synchronisation
- SNR degrades with loss

OOK

- Direct modulation of laser

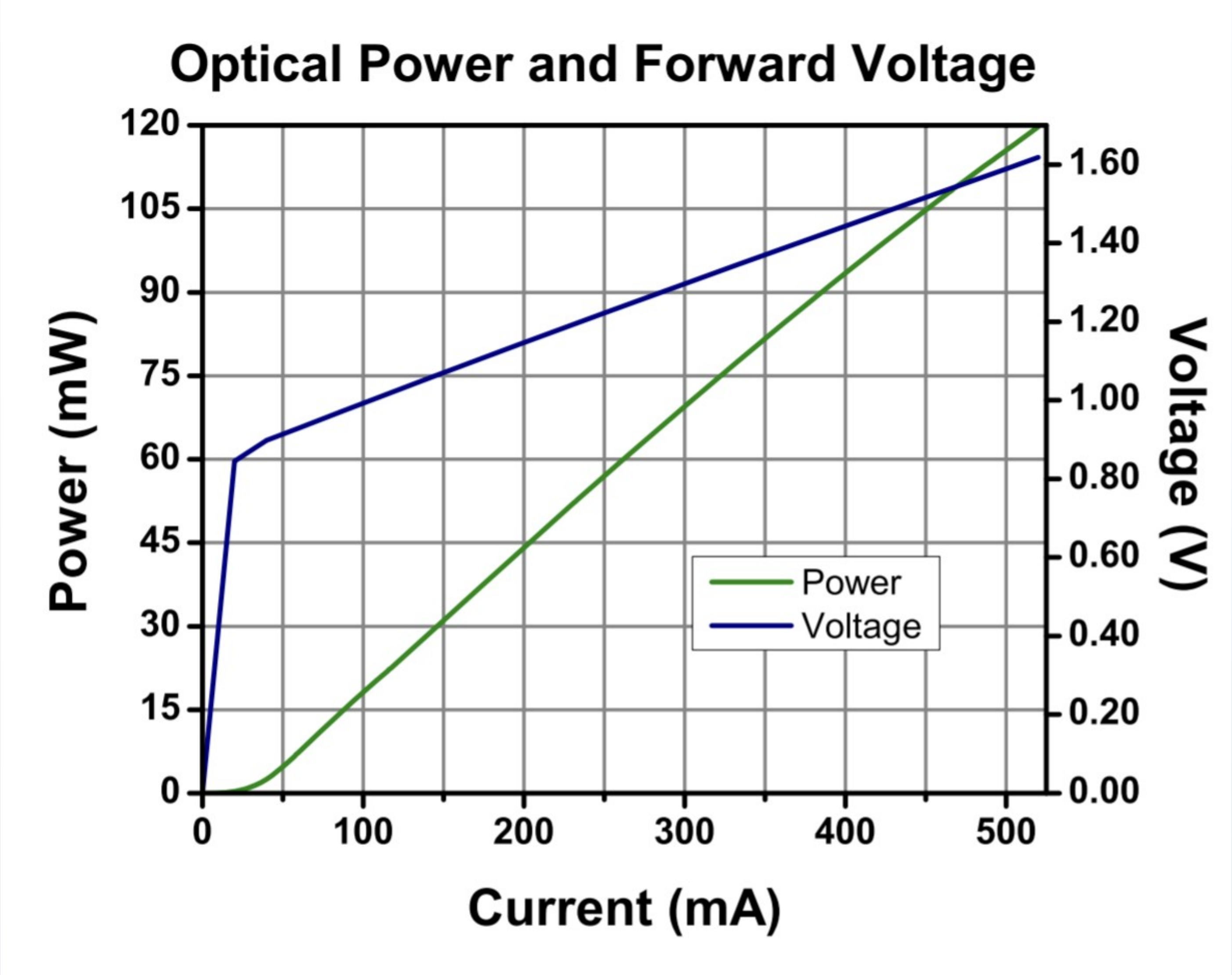
Or

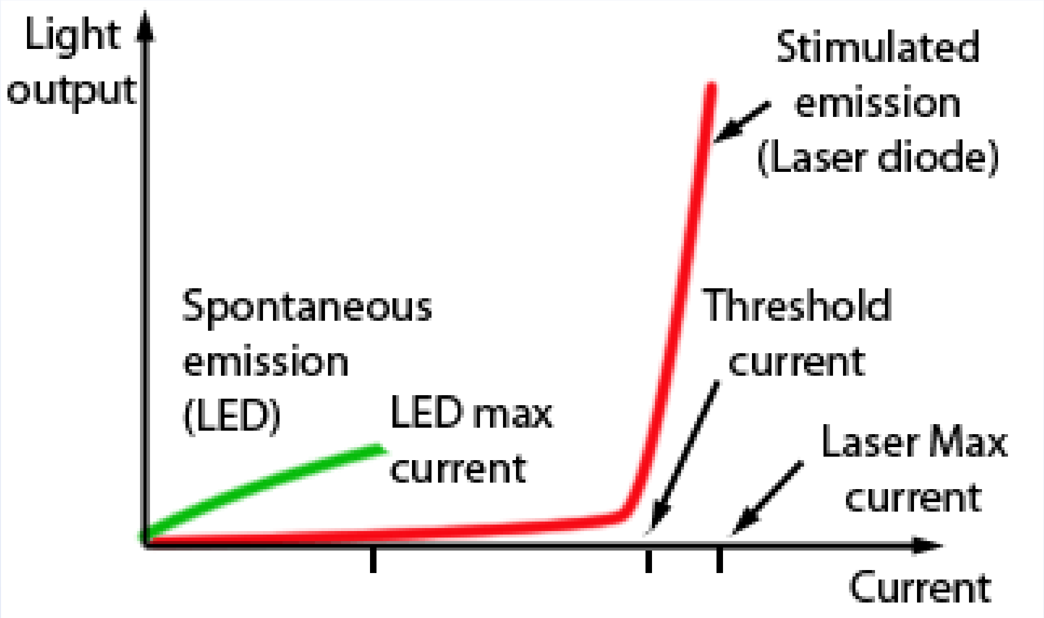
- External amplitude modulator



OOK is also called Binary Amplitude Modulation

Recap: Laser threshold





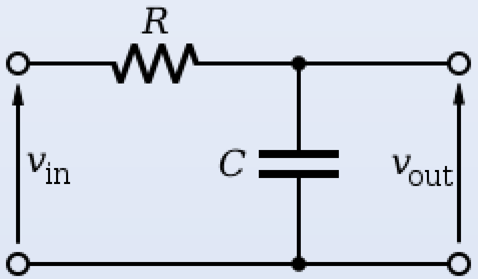
FPL1009s datasheet

Direct modulation for OOK

- Laser diode operated by a current source
- Off state: Just below threshold
- On state: Operating current

Using an off state of 0 mA is slower and more energy consuming

Max modulation bandwidth given by Capacitance (C), Inductance (L) and Resistance (R). Which form a filter.



Simplest low pass filter.

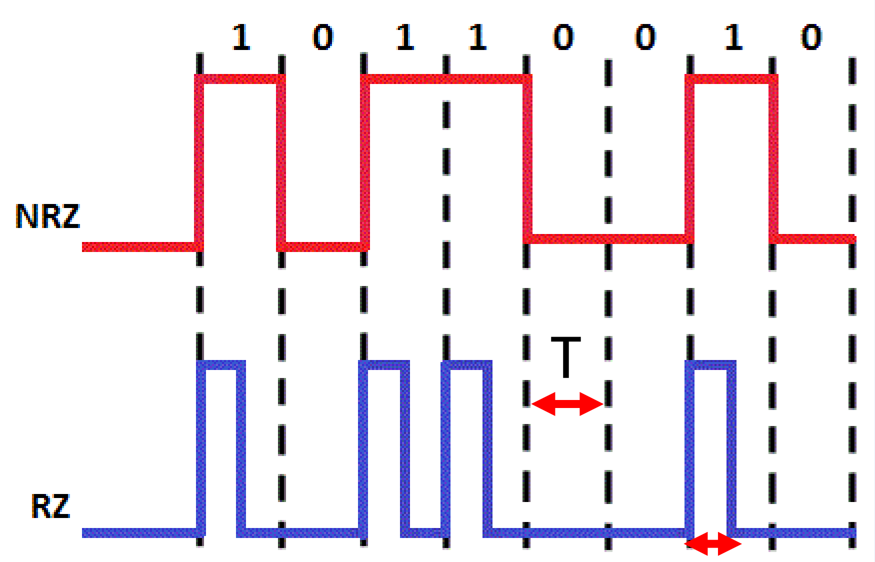
Cut off frequency (-3dB) is

$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC}$$

OOK formats

NRZ: Non Return to Zero. Pulse representing 1 stays in the high state for the entire clock cycle.

RZ: Return to Zero. The 1 pulse returns to the zero state within the clock cycle.



τ_1

NRZ has narrower spectral bandwidth

RZ can have better performance at high data speed, and easier for clock recovery

Why is this?

OOK formats

Average transmitted power

Small p: probability of 0 or 1

Duty Cycle

is the duty cycle
D=1: NRZ code
D~0.3 – 0.5 for RZ code

Typically we have equal number of 0s and 1s

Because of the usually non-zero values of P_0, the light is not completely ‘Extinct’.

OOK formats

‘Extinction Ratio’ is defined as

Optical modulation amplitude is defined as

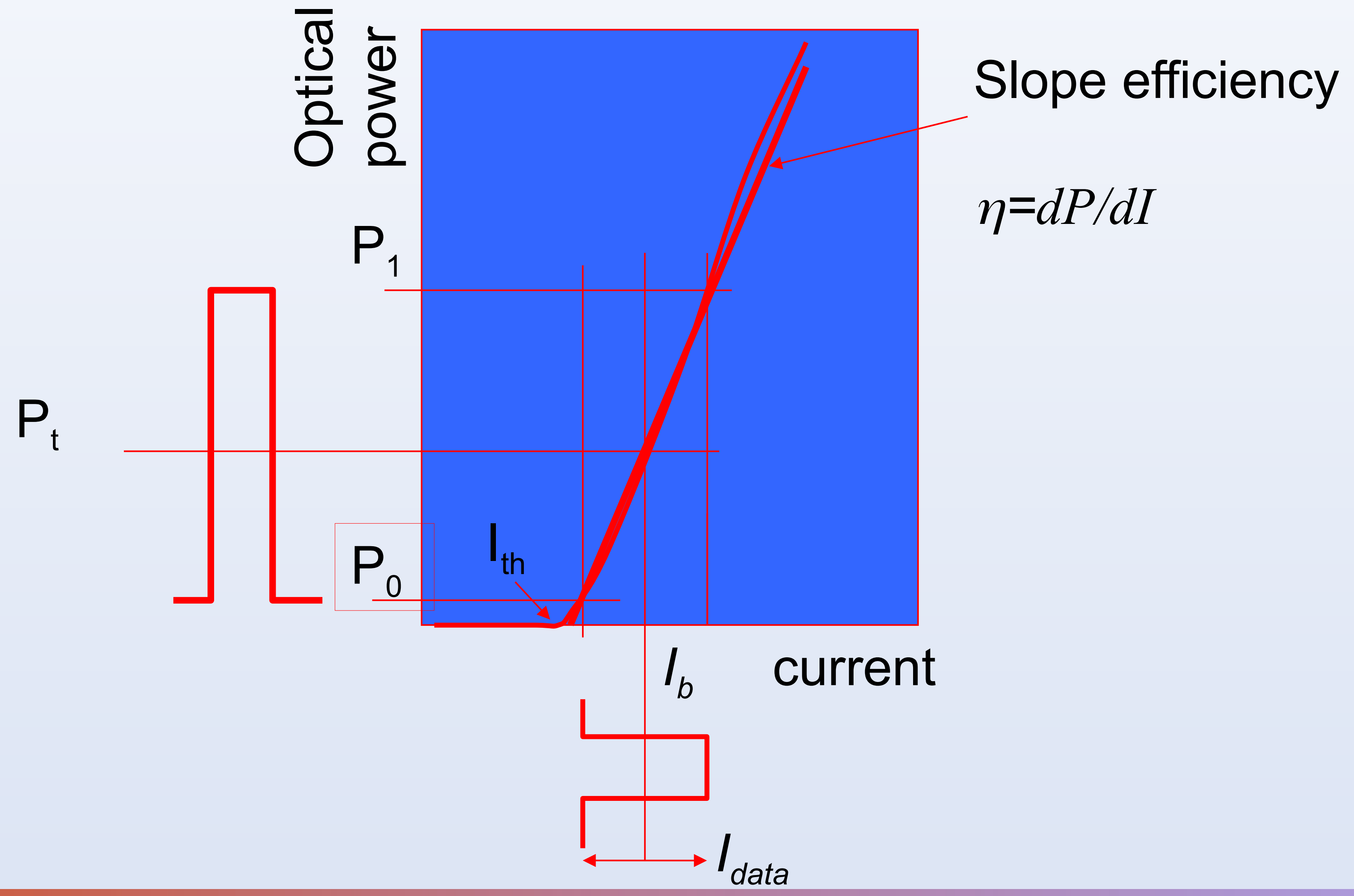
general (NRZ)

Prove this statement and derive the equivalent for RZ

OMA is the actually useful signal amplitude

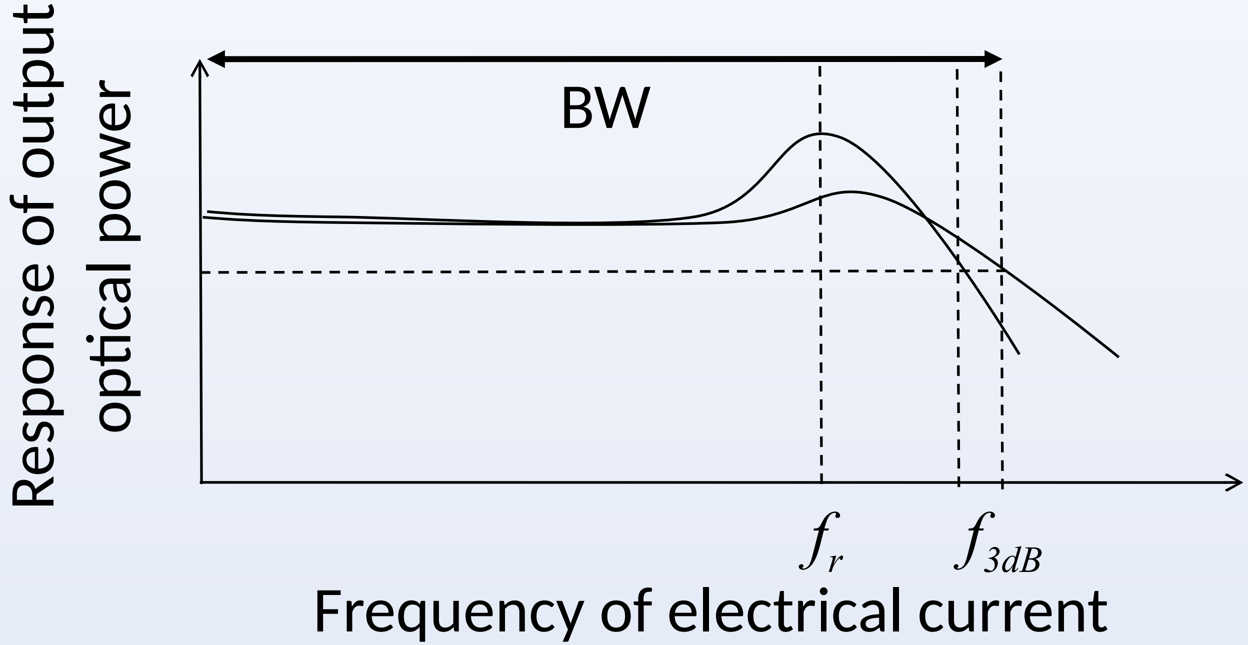
Do not confuse OMA with OAM Optical Amplitude Modulator is a device

OOK Direct modulation of a LD



OOK Direct modulation of a LD

LDs have limited modulation response bandwidth



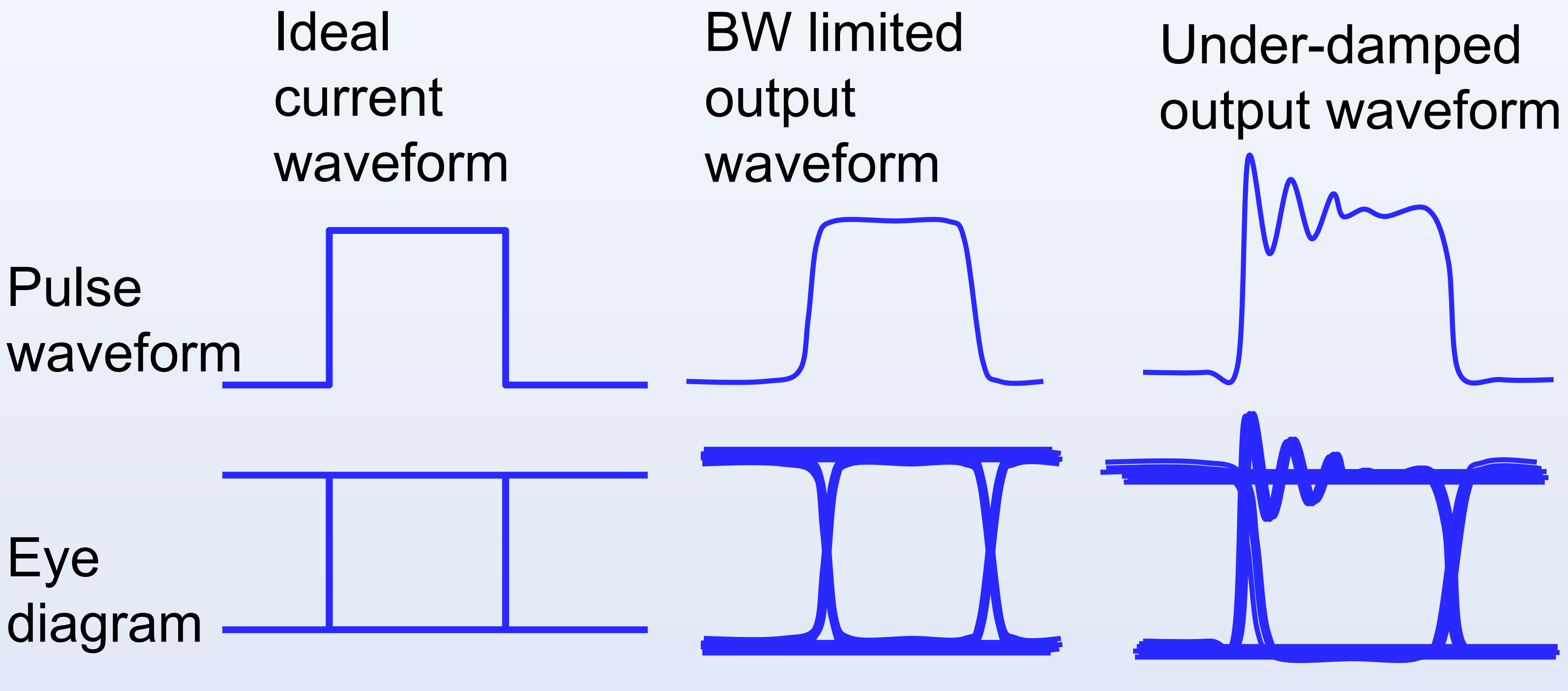
It's frequency response typically exhibits a 2nd order filter response

- a resonance peak fr
- 3dB BW of up to 20-30 GHz can be achieved with carefully engineered LDs

Height of peak should be controlled

- Max 3dB BW is obtained at 'critical damping'

OOK Direct modulation of a LD



More about eye diagrams tomorrow

- Waveform distortion caused by
  - BW limitation: slow rising and falling edges
  - Relaxation osc.: resulting in thick ‘eye-lid’ in eye-diagram

OOK Direct modulation of a LD

- Low cost😀

- Low waveform quality😣
- Low spectral quality😣

- Can only be used for short-reach optical communications links

Using external modulators

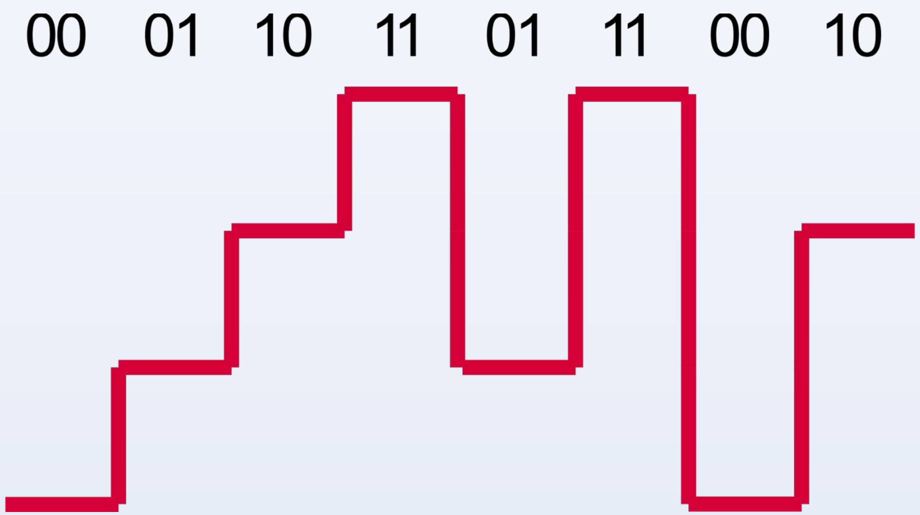
We will discuss how modulators are used in the Asynchronous Lecture Week13_Lecture_011_Async_Modulators

This will draw on knowledge form optoelectronic devices and other courses.

ASK

Each amplitude level represents one symbol

- ✓ Better than OOK
- ✓ Simple receiver



Baud rate = number of symbols (L) per second

Data rate = Baud rate * $\log_2(L)$

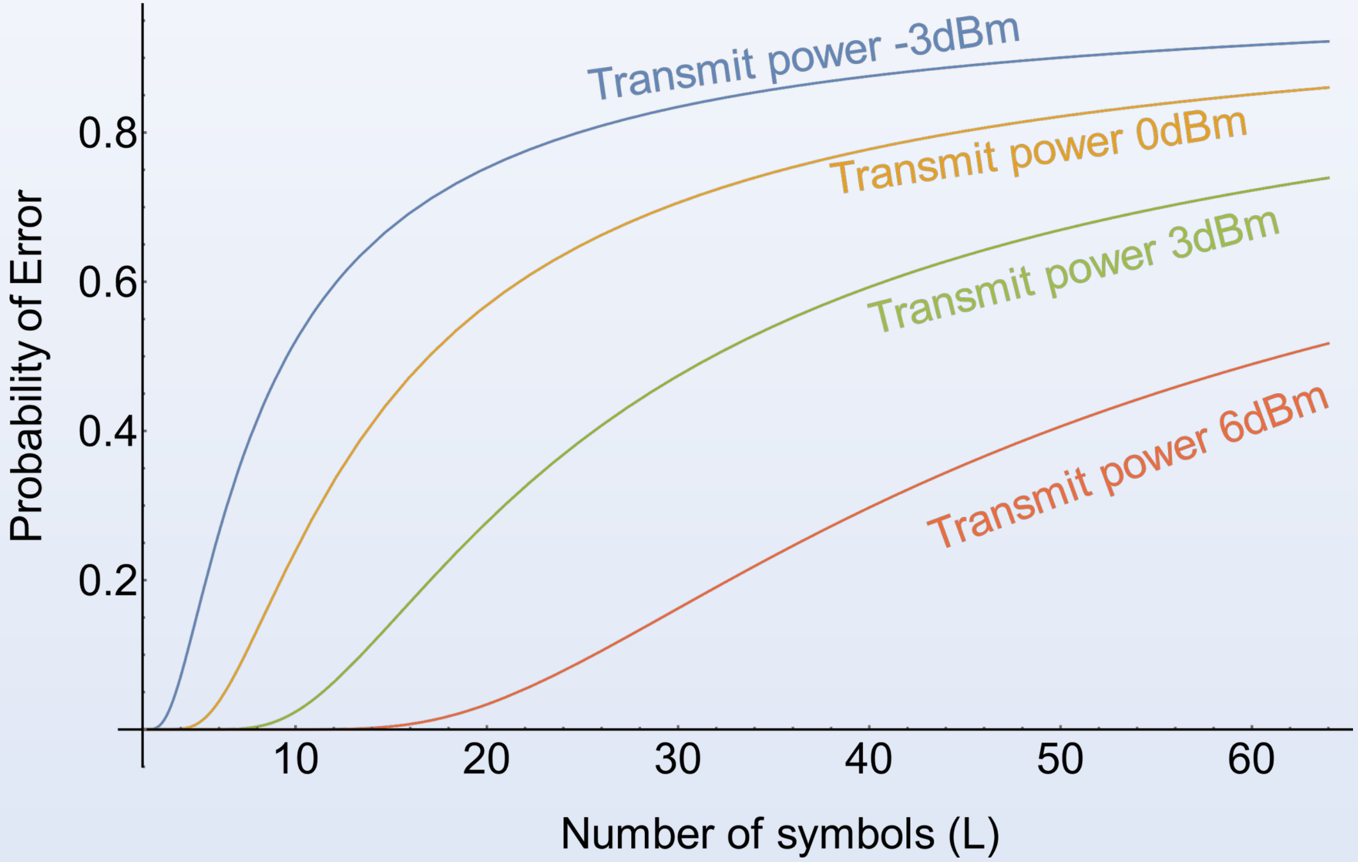
- Increased error probability (lower SNR)

We will calculate this error rate when we study demodulation and receivers

ASK

4 symbols is typically a good choice

You will learn how to calculate this soon



Graph calculated with common values of detection noise & loss. Assuming no intersymbol interference.

ASK

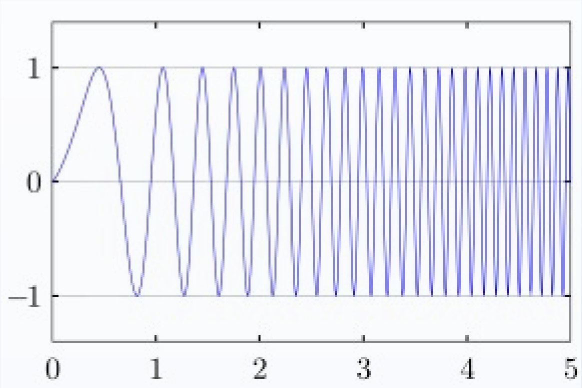
What laser do we need?

- High carrier frequencies (either modulated lasers or high repetition rate pulsed lasers)

Where is it used?

- Ethernet protocols (E.g., EEE 802.3ba 100Gb/s & IEEE P802.3bs 400Gb/s standards)
- <10 Km or <40 Km links
- ≈ up to 25 GBd (Giga baud)

Frequency Chirp



Frequency chirp: Rapid change in (modulation) frequency

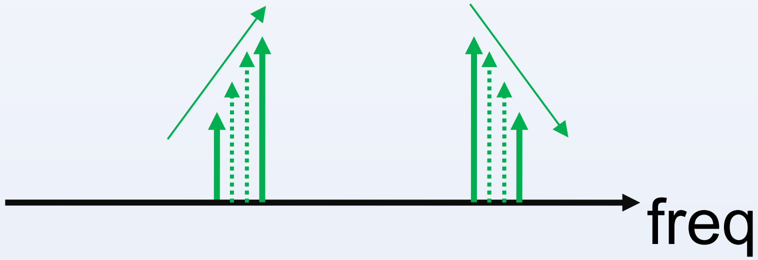
Two types:

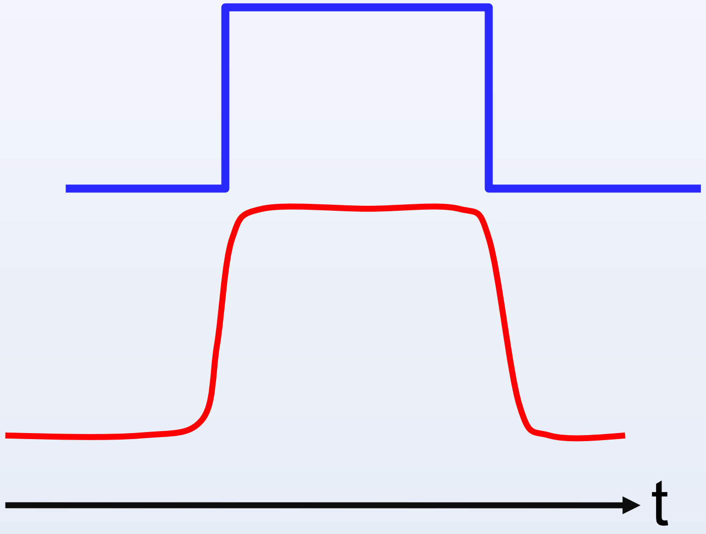
Change in modulation: due to imperfect shape of electric pulse.

Change in wavelength: due to refractive index dependence of a semiconductor on the current flowing through it. This changes the optical path length of the laser cavity.

Also called parasitic phase modulation

Frequency Chirp





Input current waveform

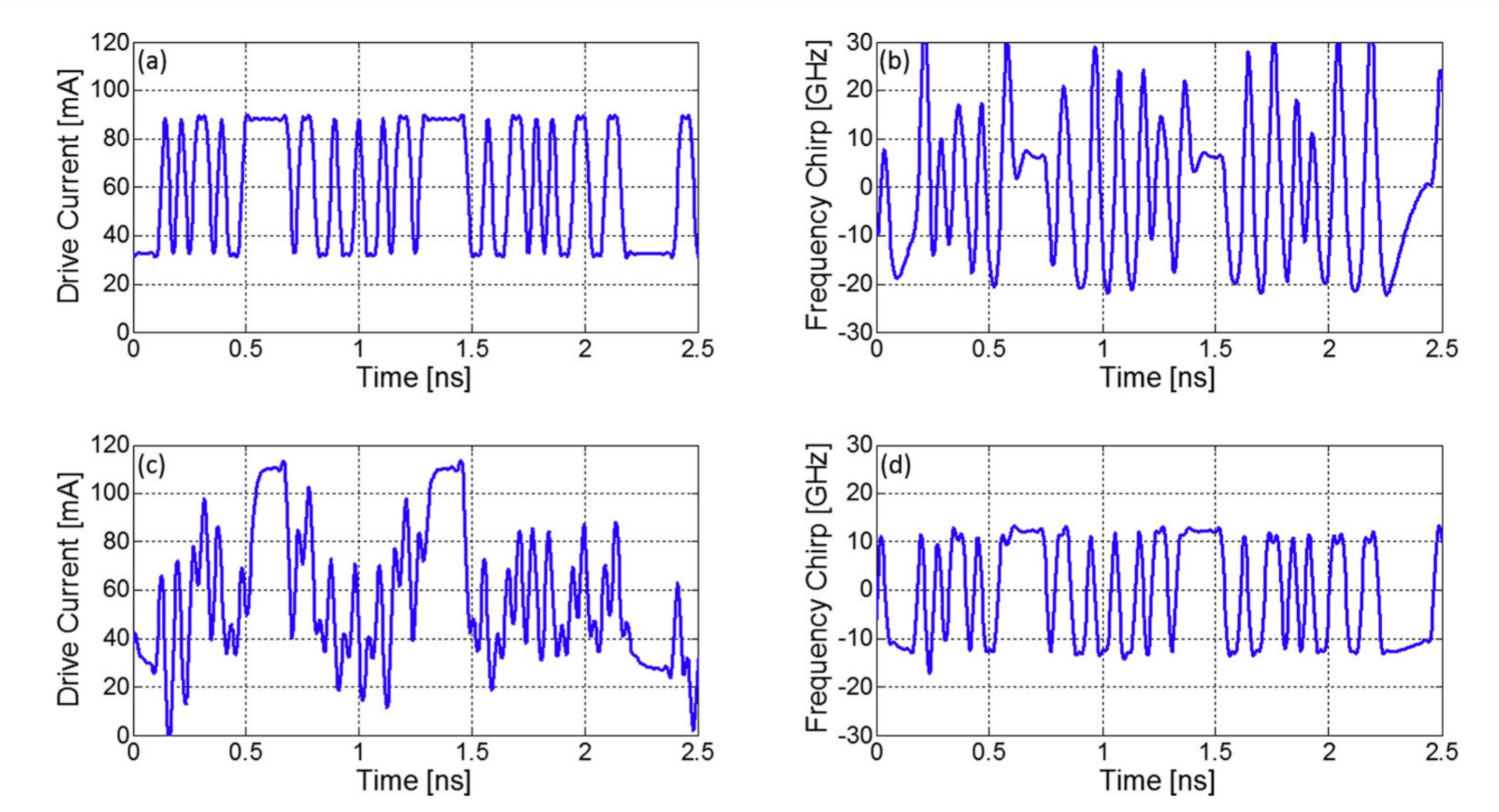
Output power waveform

Output frequency chirp

- Chirp: optical frequency change accompanying amplitude change
- In direct modulation, Chirp is caused by current change, as n is function of current I
- Typical value $\mathrm{d}\nu / \mathrm{d}I \sim$ 120GHz/mA
- Chirp broadens the optical spectrum
- Chirp is bad for transmission because of fibre dispersion (discussed later)
- This chirp happens to all lasers: even DFB laser will have chirp under direct modulation

Frequency Chirp

Fix frequency chirp by modulating laser drive current



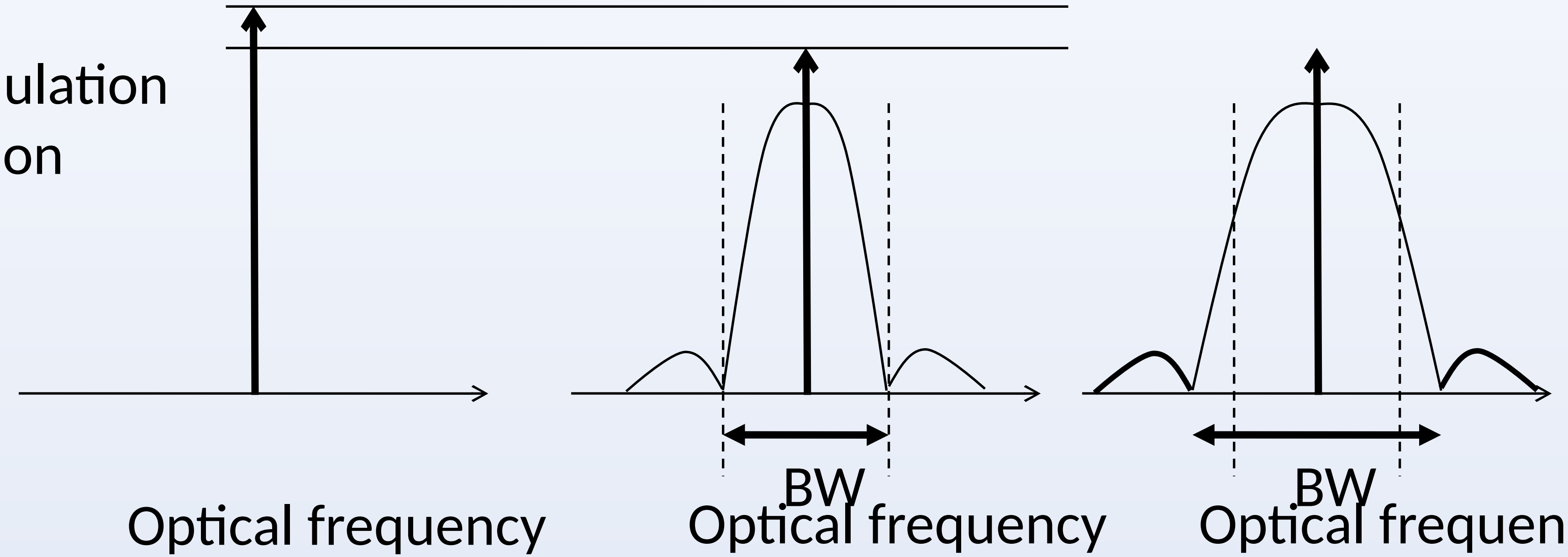
Complex fix

Strong limit on baud rate if not fixed.

A. S. Karar, et al. *Optik*, *206*, 164308 (2020).

Signal spectra

Spectrum before modulation
Spectrum is a δ-function



Spectrum after
NRZ modulation
BW = 2x (1/T)

Spectrum after
RZ modulation
BW = 2x ($1/\tau_1$)

Pure amplitude modulation will create symmetric side-bands

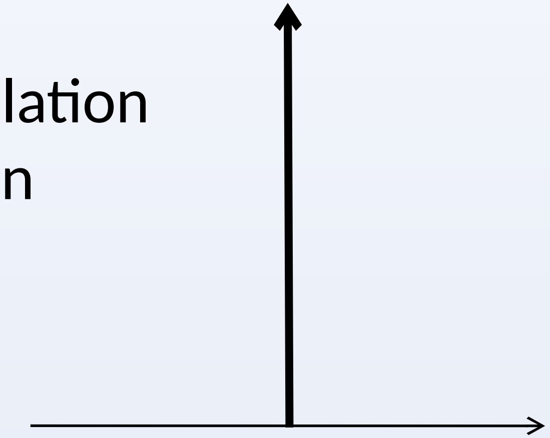
The modulated signal BW is decided by the pulse width τ: **BW$\propto$ 1/τ_1**

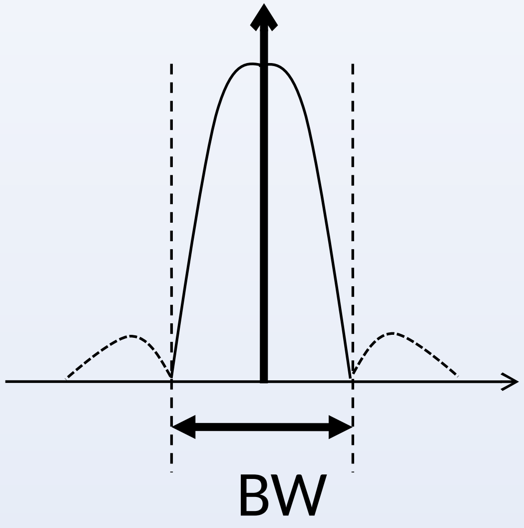
NRZ: τ_1=T, (T: data clock period) , RZ: τ_1<T

Signal spectra

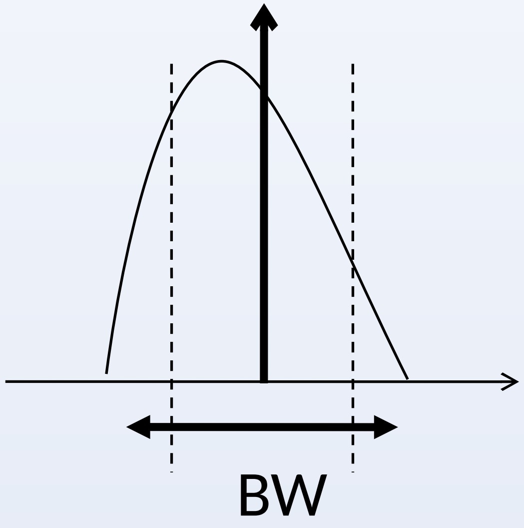
Spectrum before modulation

Spectrum is a δ-function





Spectrum after
NRZ modulation
No chirp

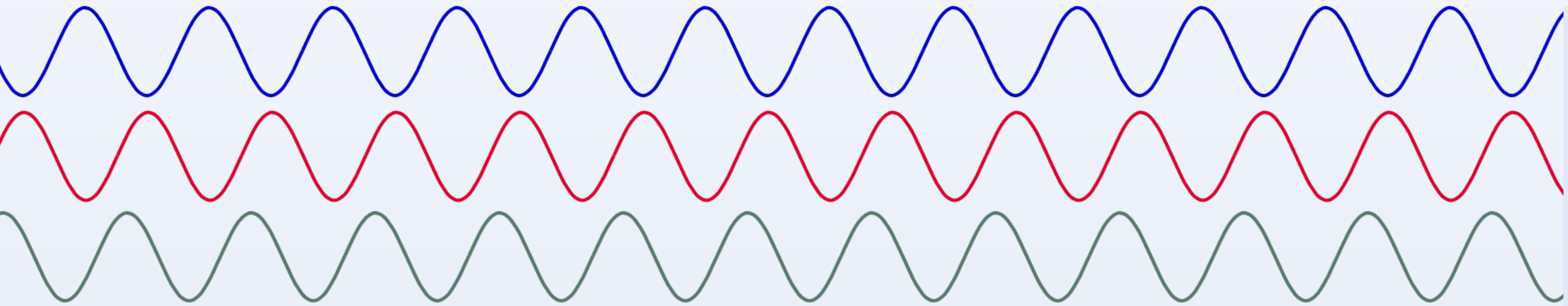


Spectrum after
NRZ modulation
With chirp

Additional phase modulation (PM) or chirp will

- Broaden the spectrum of AM signals
- Make the spectrum asymmetric

Phase

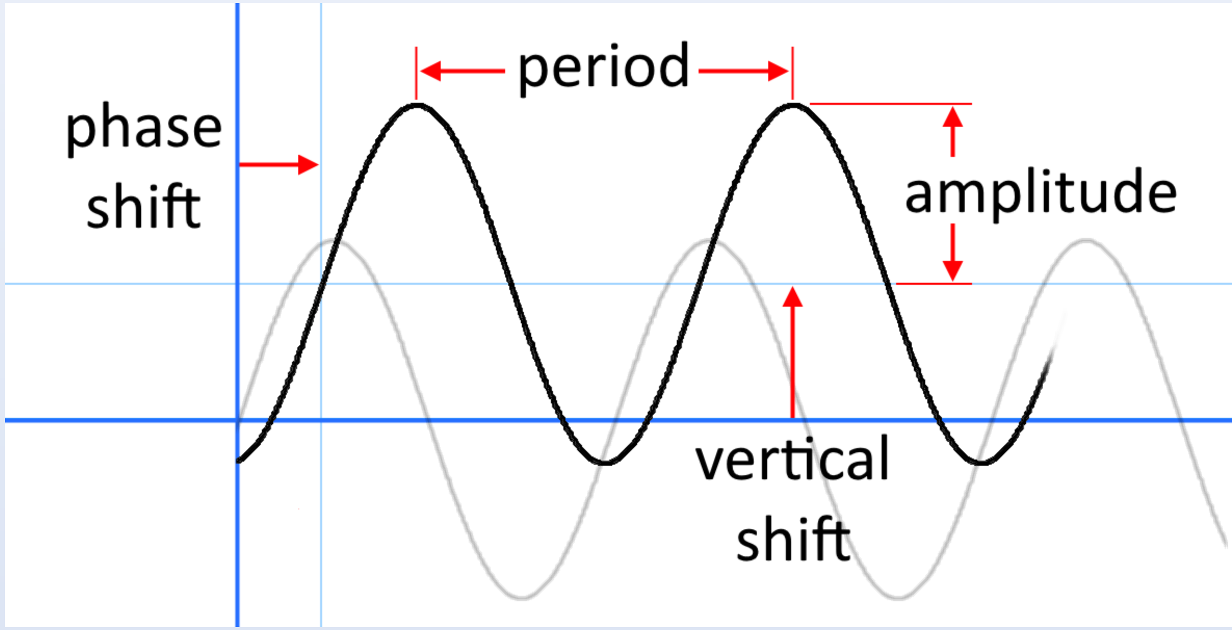


0 degree

180 deg or π

90 deg or π/2

Phase is always a relative measurement.



Phase coherence

A laser is phase coherent.

i.e. all light emitted from the laser at the same time has the same phase.

A laser’s phase drifts with time.

Phase measured by interference

Interference

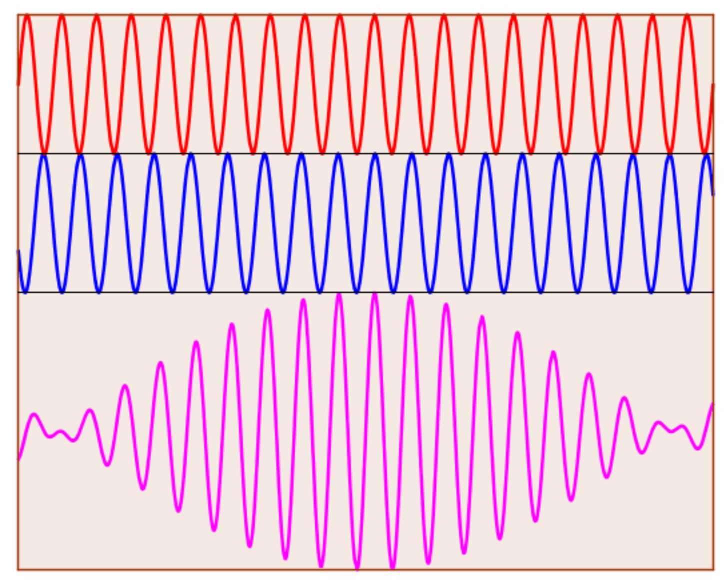
Light of same frequency and same polarisation can interfere.

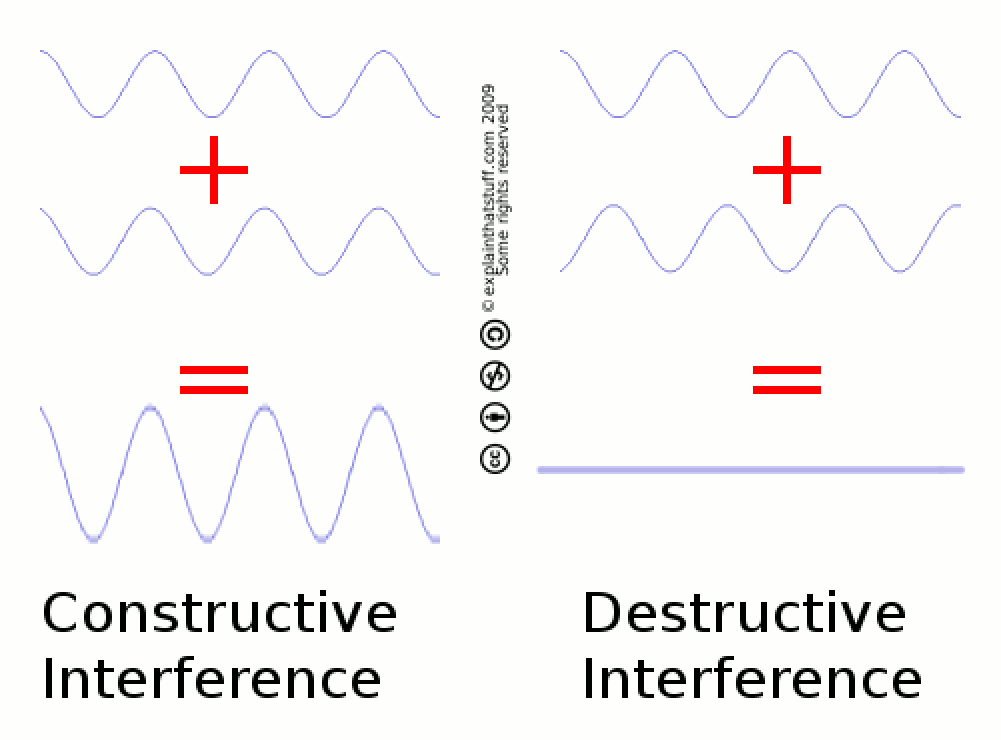
Interference is the sum of the wave equations.

Light of different frequenc eat frequency

Beat frequency is the envelope

$= |f_1 - f_2|$

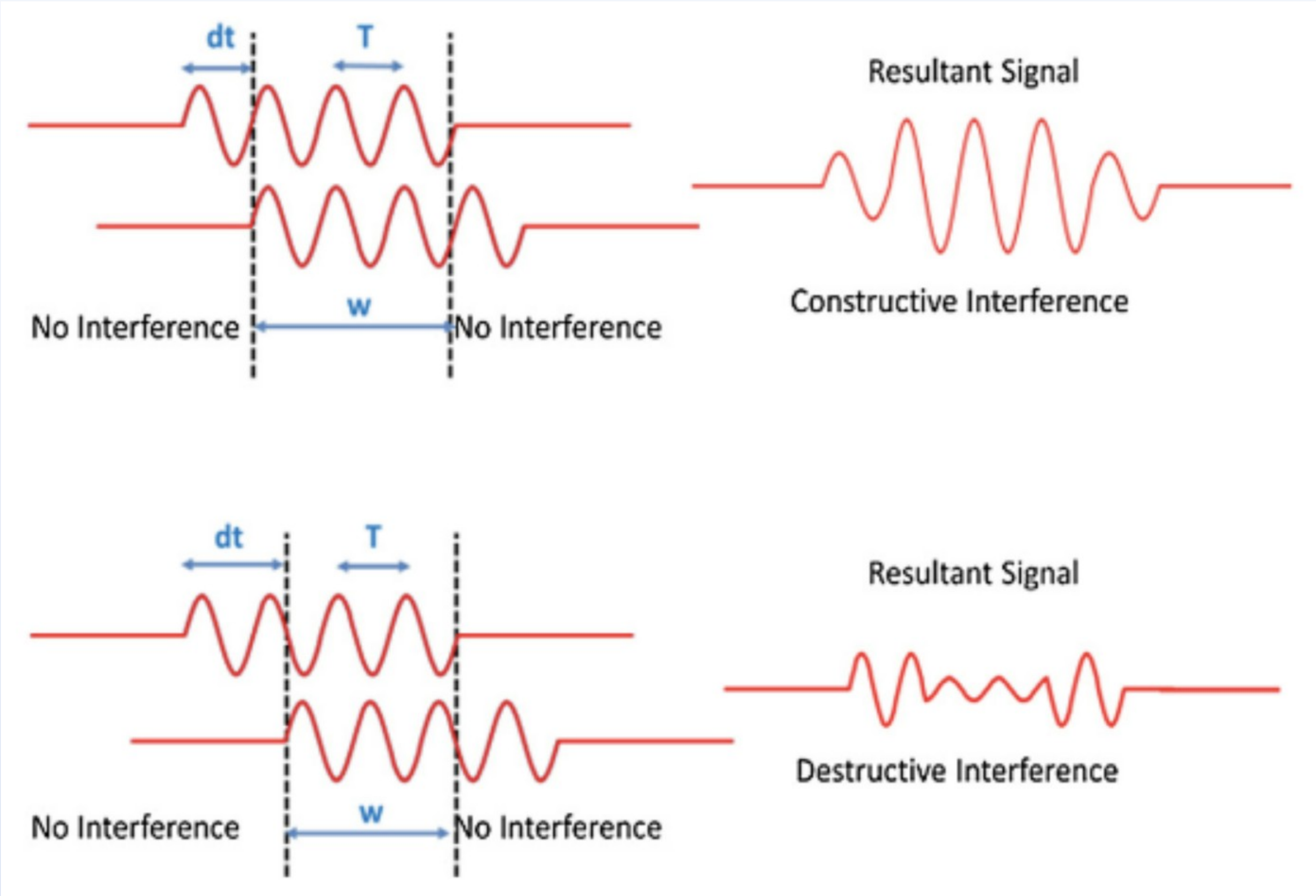




Interference

Phase changes can be detected by interference.

Interfere a reference signal and the phase modulated signal to detect phase changes.

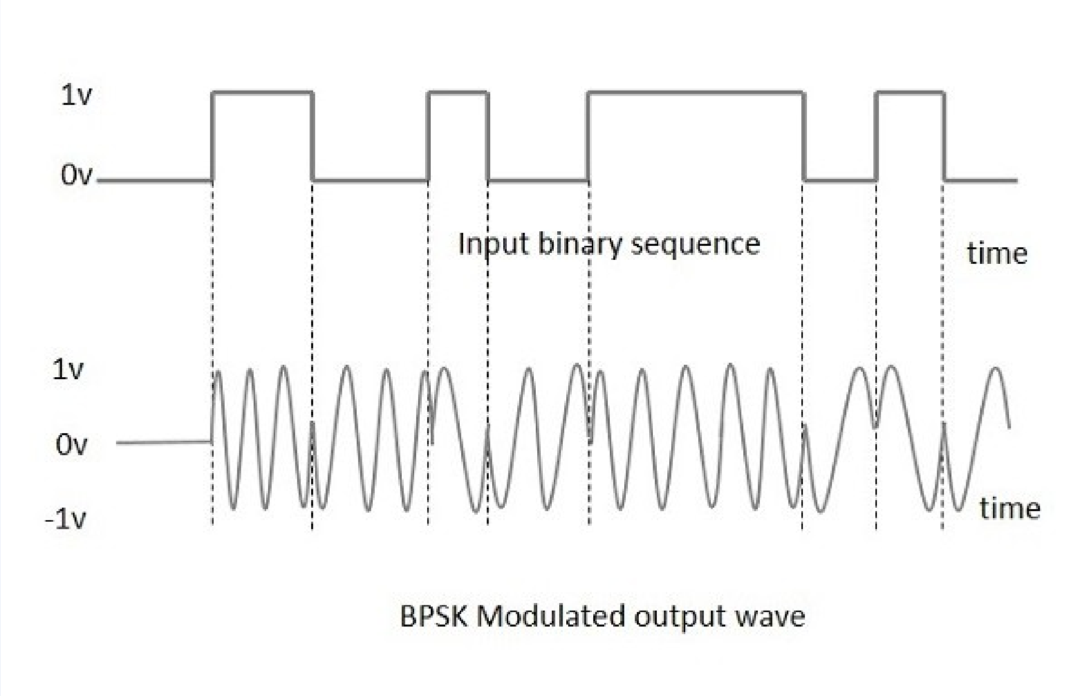


PSK

Amplitude is affected by noise and loss.

Phase of carrier wave less so.

Binary PSK ➡ L = 2 (0 ➡ 0°, 1 ➡ 180°)



- ✓ Less sensitive to noise
- ✓ Good for long distance and lossy links
- ☐ Complex signal reconstruction ➡ Needs a local oscillator at carrier frequency.

  Can you think of this before we discuss it in Week 15?

Problem

Convert a frequency difference of 100 GHz at 1550nm to the corresponding wavelength difference. State your answer in nm.

Hint: Frequency difference is $f_1 - f_2$ and is not the same as 100 GHz directly expressed in nm.

Problem

A BAM scheme uses a signal amplitude of 0dBm for 1 and -10dBm for 0. With a duty cycle of 1. Calculate the average transmitted power.

With a time period of 1ns what is the frequency bandwidth of the modulator required?

If the duty cycle was 0.2 what would be the new average power and the new frequency bandwidth required for the modulator?

Explain the difference between the frequency bandwidth of the modulator and the optical bandwidth of the transmitted signal.