Optical Sources and Transmitters

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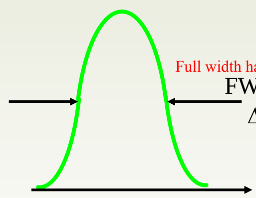
Light Emitting Diode

- P-N junction
- Forward current leads to spontaneous emission
- Very heavy doping required for high speed LEDs
- Spectral linewidth determined by temperature

LED Linewidth

Derive

$$\Delta E \sim kT; E = hf = \frac{hc}{\lambda}$$



$$\frac{\Delta E}{E} = \frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \sim \frac{kT}{E}$$

$$\Rightarrow \Delta f \sim \frac{kT}{h}; \Delta \lambda \sim \frac{kT}{hc} \lambda^2$$

- Linewidth depends on junction temperature
- $\Delta\lambda$ varies with emission wavelength as λ^2

Laser Diodes

cavity is two mirrors placed side by side parallel

- Emission wavelength essentially as for LED
- Emission spectrum depends on cavity (optical feedback) arrangements making light back and forth to amplify
- Generally several spectral lines
- Spectrum varies transiently with drive current (chirp)

more current will change the color of light because of change of spectrum

Feedback Arrangements

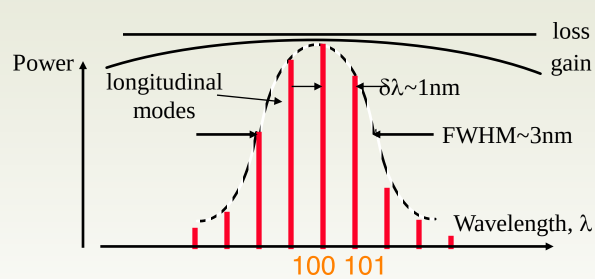
difference between DBR and DFB is the region of grating is different, DFB is on whole gain region, however, DBR is at the ends.

- Fabry - Perot cavity (FP)
  - Ends of the laser are cleaved such that the index difference between III-V material and air forms mirrors
- Distributed Bragg Reflector grating (DBR)
  - A periodic structure (e.g. index variation) at the end of gain region may serve as a wavelength-selective reflector
- Distributed FeedBack (DFB)
  - A grating may be incorporated intimately with the gain region rather than separate from it

red lines means individual emission of light

F-P Laser Spectrum

increase the current to let gain is bigger than loss, where the point is called threshold



- Longitudinal mode spacing is determined by cavity length and group refractive index
- Output power in any mode is inversely proportional to loss-gain

Both multi-longitudinal mode and single longitudinal mode diode lasers have their inherent pros and cons. Multi-longitudinal mode diode lasers are typically more straightforward and cost-effective to produce, with the added benefit of generating much higher output powers, due to the larger number of modes. On the other hand, single longitudinal mode diode lasers have a much narrower bandwidth, making them more desirable for applications that require precise knowledge of the wavelength. However, these diode lasers typically produce much lower power and are more challenging to manufacture.

refractive index of glass is 1.5

1.55 um is no-loss wavelength of silicon optical fiber

Mode Spacing

L is the distance between two mirrors

nL called optical length, the length we are interested in optical fiber

- If the material refractive index is *n*, and the length of the laser cavity is *L*, then the “optical length” is *nL*
- At resonance the cavity length must be an integer number of half wavelengths so that the reflected light adds in phase

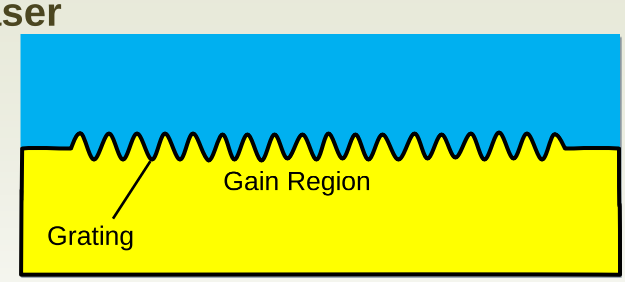
$$nL = m\frac{\lambda}{2}$$

the wave has to be added constructive so it is wavelength/2

- So for a laser with *n*=3.3, *L*=300 μm, *λ*=1.5 μm then m=1320

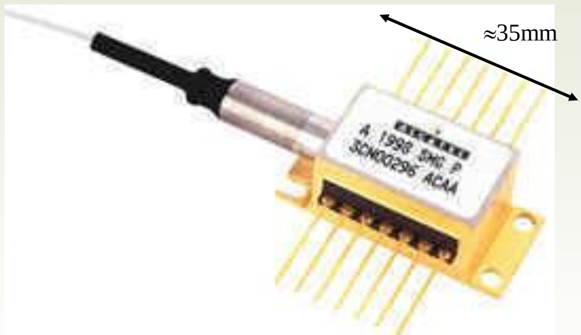
how many half wavelength in cavity indicates the how many red lines in above graph

DFB Laser

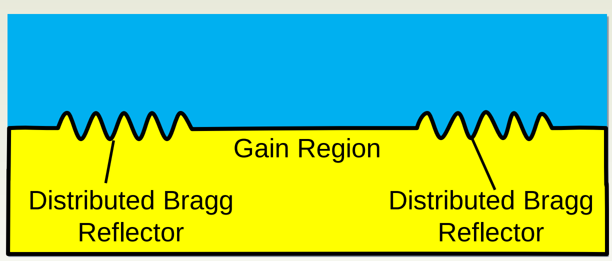


- Grating is ‘built in’ to the laser structure
- 1st-order grating means that multiple-longitudinal modes are in principle avoided
- Electrical carrier induced perturbation can result in there being two, closely-spaced emission lines - a strong side mode
- A phase step in the grating helps with sidemode suppression

DFB Laser



DBR Laser



- Distinct gain and reflector regions provide for separation of wavelength control and power control
- This helps reduce laser chirp
- Multi-section lasers with intricate bias and drive arrangements can yield very low chirp and wavelength control

Laser DC Response

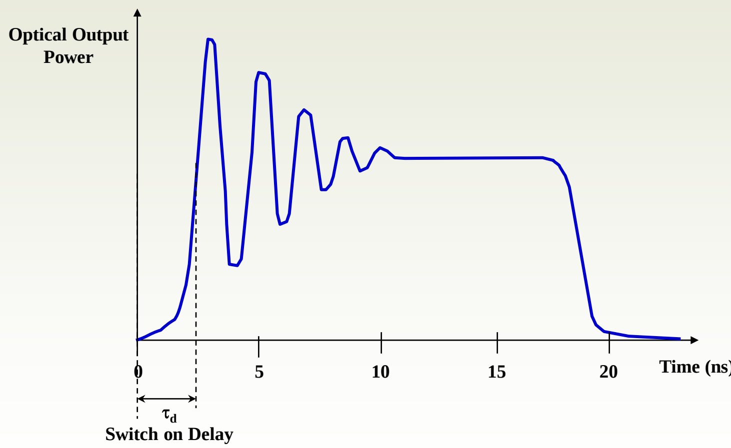
- Photon density rapidly builds up as gain begins to balance loss
- Lasing occurs at threshold; beyond this carrier density is clamped with additional carriers consumed in photon generation

Laser Dynamics

- Switch-on delay t_d
- Transient oscillation at switch-on
- Laser resonant frequency, f_0
- Maximum small signal AM bandwidth, f_{max}

modulate so it can send maximum bits

Laser Dynamics



Switch-on Delay

$$t_d = T_{eff} \ln\left\{\frac{I_{on} - I_{off}}{I_{on} - I_{th}}\right\}; \qquad I_{off} < I_{th} < \left(I_{on} + I_{off}\right)$$

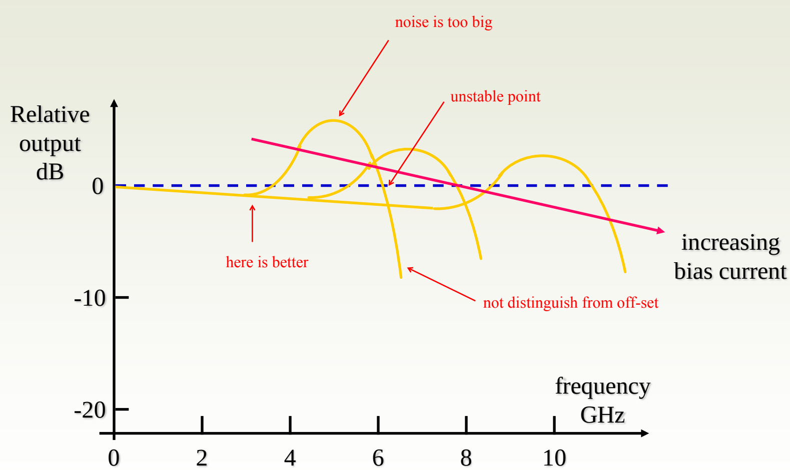
- I_{off} is DC bias, I_{on} the pulse drive
- $t_d \sim T_{eff} \sim$ nanoseconds unacceptable
- Minimise t_d by biasing at or above threshold
- Achieve delays ~ 100 ps

Resonance Frequency

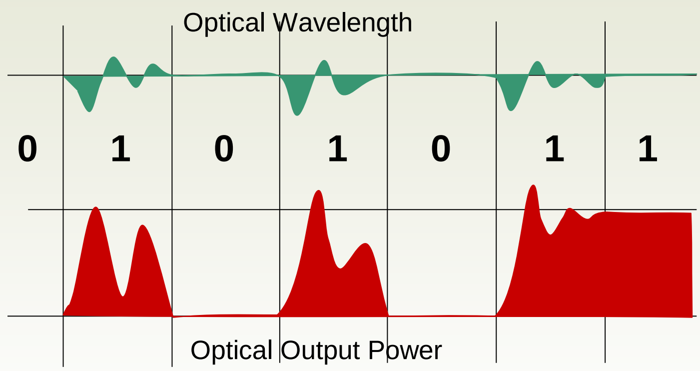
$$f_0 \propto \sqrt{P}$$ power of light

- Laser resonance frequency increases with √(P)
- Damping influences achievable f_{max}
- "Bulk" quaternary devices would have f_{max}~15 GHz but MQW structures can improve on this (> 20 GHz)

Laser frequency response



Laser Transient Response



- Output ‘on’ power ~ 5 mW
- ‘Patterning’ can be seen in the output response
- Peak-peak chirp typically ~ 0.1 nm - 0.5 nm

Laser Partitioning & Chirp

- Multi-longitudinal mode lasers suffer from ‘partition noise’ - the distribution of the optical power between the various modes fluctuates with the emission at any time instant varying markedly from the ‘time average’ spectrum
- Even for ‘single-frequency’ lasers changes in drive level result in fluctuations in carrier density, changing the gain and refractive index.
- These two effects result in a variation of the laser emission wavelength under modulation, known as ‘chirp’

External Modulation

- Directly modulated DFB lasers suffer from frequency chirping which can prove a dominant limiting factor in the presence of fibre dispersion
- External modulation can largely eliminate this - although it should be noted that an external modulator may itself induce chirp to some degree
- There are many possible forms of external modulator, with the Mach-Zehnder interferometer modulator,the electro-absorption modulator and a form of semiconductor optical amplifier being particularly widely used

Electro-absorption modulator

- Broadly similar to a laser diode in structure, with active layer and blocking layers
- Unlike the laser it is operated in reverse bias mode
- The bandgap reduces slightly as the reverse field increases, so that light at a wavelength close to the band edge experiences attenuation by absorption which increases with reverse bias
- Since the EA modulator relies on varying the bandgap of the active material it introduces wavelength chirp
- EA modulators can be integrated with lasers to produce a single, stable monolithic transmitter

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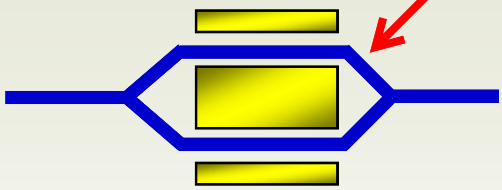
can have no chirp

like optical fiber, wave drives inside

Mach-Zehnder Modulator - 1

no chirp at all



- Light in the waveguide on an electro-optical substrate (e.g. Lithium Niobate) splits into two branches
- Electrodes induce differential phase variation between the two paths
  by changing speed of wave
- On recombination interference occurs, which can be changed from constructive to destructive by varying the electrode voltages
- The output varies cosinusoidally with phase difference, with $\Delta\varphi$ linearly related to voltage for a 'linear effect' device

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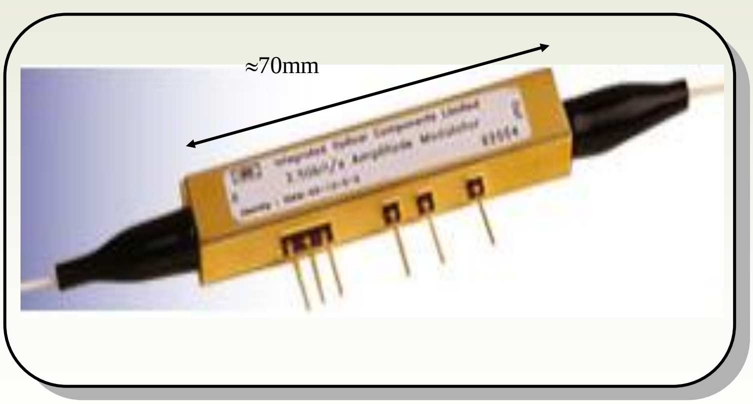
Mach-Zehnder Modulator - 1



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Mach-Zehnder Modulator - 2

- The voltage to achieve extinction is V_π, corresponding to $\Delta\varphi=\pi$
- If the device is not ‘balanced’ then chirp occurs
- Modulation bandwidth is limited by the extent to which the electrical and optical velocities can be matched to reduce ‘walk off’

optical feedback

SOA Modulator

- A semiconductor optical amplifier (SOA), sometimes referred to as a Semiconductor Laser Amplifier (SLA) is essentially a Fabry - Perot laser diode with the facet reflectivities suppressed to avoid optical feedback
- Residual reflectivity, polarisation sensitivity and relatively short lifetimes have hampered the application of SOAs as main amplifiers
- They are useful, though, for modulation and processing applications out to a few GHz

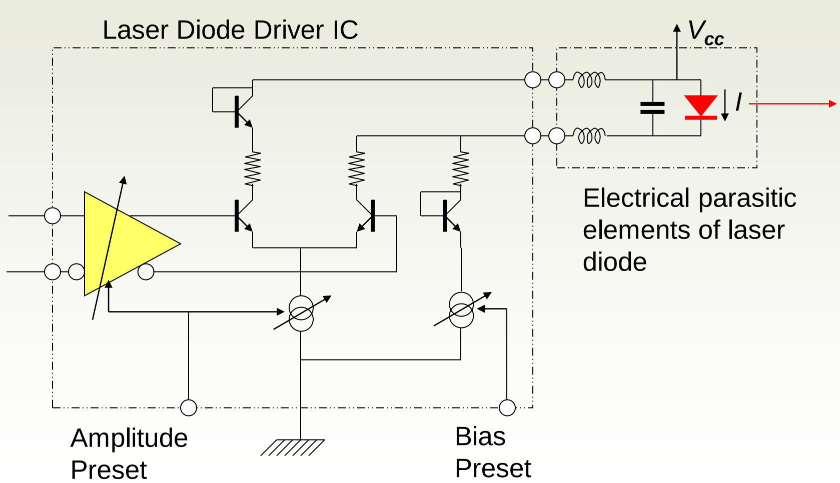
Optical Transmitters

laser is current operator device, modulator is voltage operator device

chirp

- DFB laser: f_{max} ~12 GHz, α'~3-5, I>50 mA, R~5 Ω
- MQW DFB laser: f_{max} ~ 20 GHz,□ α'~2, I>50 mA, R~5 Ω
- EA modulator: f_{max} ~ 40 GHz, α'<1, V~1.5 volts, C~0.1 pF
- M-Z modulator: f_{max} ~ 50 GHz, α'~0, V~10 volts, R=50 Ω
- DFB and EA have chirp of opposite sign so that net chirp can be controlled or cancelled

DC Coupled Laser Diode Driver



Laser Drive Circuit Practical Principles

- Drive voltage can be lost at high frequencies due to the length of a transmission line to the laser.
- Impedance mismatches in the electronic transmission path to the laser cause waveform deterioration.

Laser Drive Circuit Design

- When designing a laser drive circuit for the highest speeds it is necessary to take account of the behaviour of the laser under the various drive conditions.
- The impedance of the laser changes with frequency so the matching to it must also be designed to change.
- This can be done by representing the laser as an equivalent circuit which incorporates the elements within the rate equations.
- Then a circuit simulation CAD tool such as, SPICE, can be used to optimise the drive circuit to open the eye pattern.

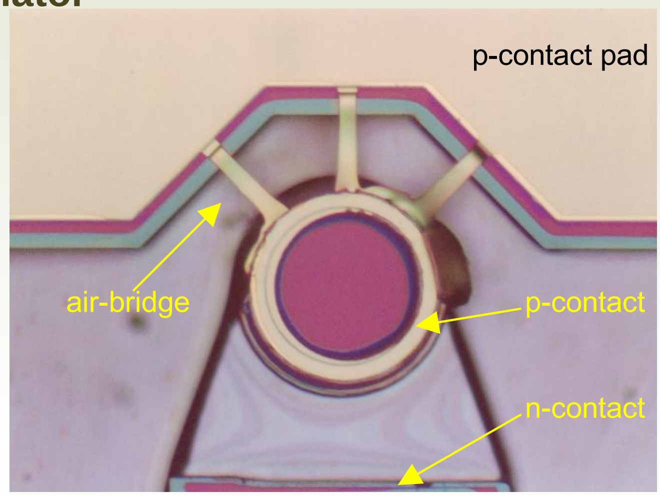
Laser Diode Parasitic Impedances

- Parasitic impedances arise from wire bonds, ribbon connections
- They may take the form of self inductance of a bond wire, or mutual inductance between bond wires or capacitance of bonding pads.
- Multiple gold wires can be used to reduce the inductance.
- Ribbon connections reduce the value of the inductance even further and consist of a conductive ribbon above a ground plane.

Laser Diode Parasitic Impedances

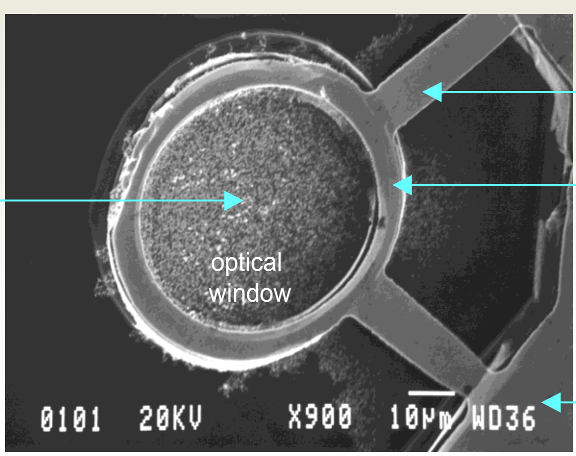
- At high frequencies these become very important and cannot be neglected in the design of matching networks or laser diode drivers.
- Parasitic inductance may be of the order of 0.2 to 0.5 nH. Inductances must be reduced below 0.4 nH if large oscillations are to be avoided which may cause transmission errors. The exact threshold value depends on the rise time of the applied signal.
- Parasitic capacitances may be of the order of 0.1 pF.

Photograph of MQW QCSE Reflective Modulator



SEM Photograph of an air bridge to a QCSE modulator

residual photoresist and Ti metal

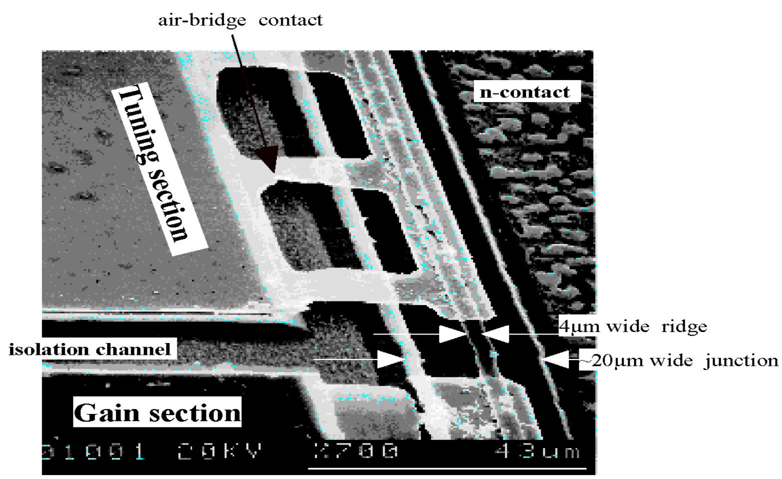


air_bridge contact

p-contact

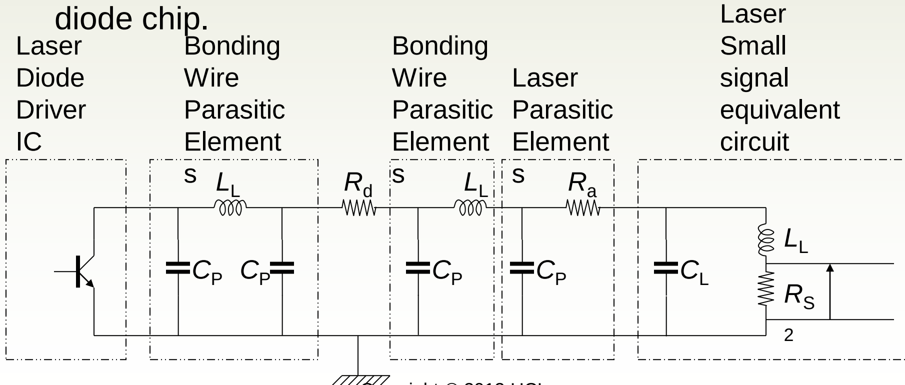
contact pad

SEM photograph of an air bridge to an MQW QCSE Tuneable laser



Electrical parasitic elements

- R_d is a series resistance added to damp unwanted resonances.
- The laser driver IC die is connected via a bond wire to the chip resistor, R_d and via another bond wire to the laser diode chip.



laser

wire

Electrical parasitic elements

- Differential laser driver designs reduce the effect of power supply ripples.
- However, even in these when a driver switches state from low to high and high to low, the output signal of the driver is degraded since a sudden current ripple is produced
- This current ripple appears in the interconnections to the power supply due the parasitic inductance of the interconnections.

Electrical parasitic elements

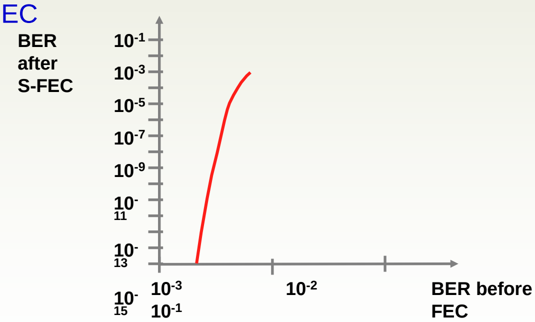
- In this case the inductance and resistance of wires from the external power supply to the driver chip internal power supply act as parasitics as well as those of the bonding wires.
- Decoupling capacitors should be placed between the power supply rail and earth and positioned near the internal power supply to provide charge during switching.
- Larger capacitance values (> 7 nF) significantly improve the output signal and can be embedded into the laser driver IC design as an on-chip decoupling capacitor.

Forward Error Correction, FEC

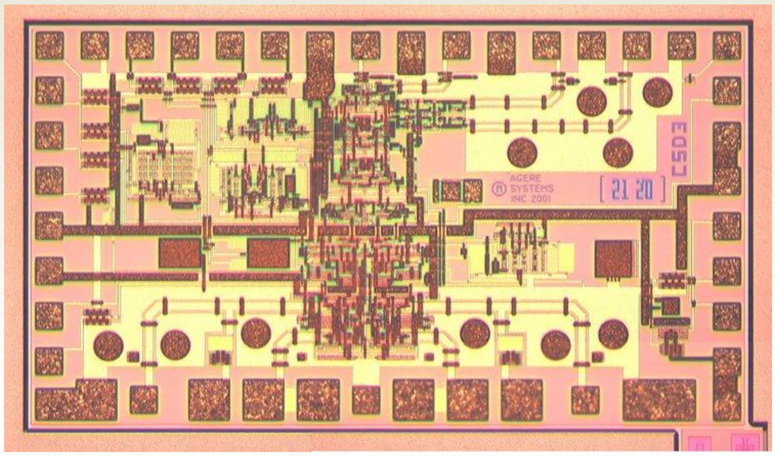
- FEC reduces 'output' BER
- Popular code is Reed-Solomon (RS)
- It slightly increases the actual line bit rate but provides an improvement in power budget.

Second Generation FEC (S-FEC) performance

•A BER of 2 x 10^{-3} before Second Generation FEC becomes 1×10^{-15} after S-FEC



10.7 Gbit/s Laser Driver Die



Integrated Transmitter Modules

- More recently there has been a trend for manufacturers to combine optical elements within a single module or on a single substrate.
- Laser - modulator combinations are the most common but also other elements may be combined.
- They include modulator (electro-absorption, Mach-Zehnder), tuneable laser, Semiconductor Optical Amplifier (SOA), wavelength converter, Transmitter-Receiver Device (TRD), Vertical Cavity Surface Emitting Laser (VCSEL), demultiplexer, semiconductor laser pump source for Erbium Doped Fibre Amplifier.

Laser-Modulator Module Example

- Monolithic integration of a DFB laser and an electro-absorption modulator driven by a high-speed GaAs integrated circuit within the module package.
- The use of an external modulator gives much lower chirp than a directly modulated DFB laser
- Low drive voltage < 2V.
- Internal optical isolator.
- DFB laser wavelength may be selected around 1.55 μm.

Laser-Modulator Module Example

- 12 dB extinction ratio.
- -3 dB Bandwidth of 9 GHz.
- 10 GBit/s operation demonstrated over 80 km.
- Chirp parameter of 0.3
- Light extinction efficiency 10 dB/V
- MOVPE deposition
- Package also contains monitor photodiode, thermistor and TEC.

Optical Transmitter Module Example

- DFB laser
  - buried 5 MQW InGaAs/InGaAsP heterostructure
  - pn blocking layers
  - 350 μm long.
  - 4 mW, extinction efficiency 10 dB/V, -3 dB Bandwidth 16 GHz.
  - α parameter was 0.3 to 0.4
- Modulator
  - high mesa ridge easier to impedance match
  - AR coated
  - 200 μm long.

Optical Transmitter Module Example

- Driver IC
  - 2 V_{pp} output.
  - 2 stage differential. First stage linear amplification, second stage limiting amplification.
  - InGaAs/GaAs stined Buried P-layer MESFET with gate length of 0.2 μm.
  - Rise and fall times were 32 ps and 30 ps. for 20 to 80% 15 dB gain
  - -3 dB bandwidth 9.5 GHz.
  - Power consumption 1.8 W.

Structure of Integrated Laser - Modulator Module

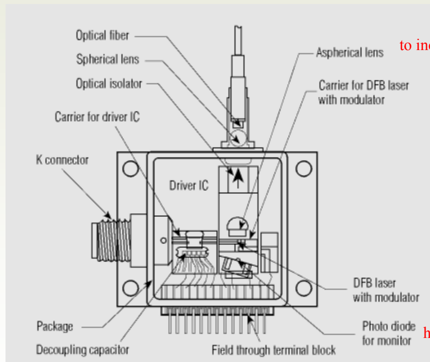


Figure 3: Schematic structure of an optical transmitter module (top view)

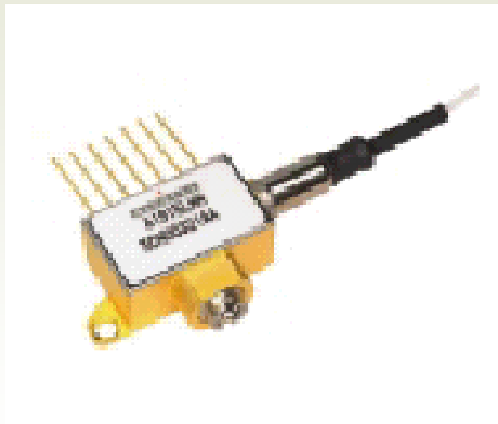
to increase tolerance such as dust or temperature

has an angle to prevent laser go back

Structure of Integrated Laser - Modulator Module

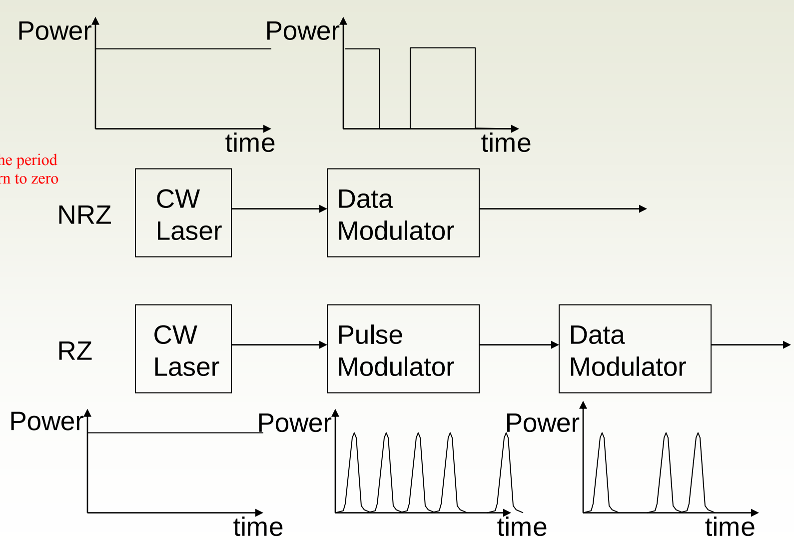
- Module size 22 x 24 x 12 mm^3.
- Alumina carriers with high frequency transmission lines.
- Short bond wires to minimise parasitic inductance
- Power supply decoupling capacitor for stability.
- 50 Ω input impedance due to 50 Ω termination resistor near chip.

Integrated Laser - Modulator



NRZ and RZ modulation

within the period
not return to zero



RZ modulation systems