Lecture 7: Pulsed and Mode-locked Lasers. Introduction to Modulators

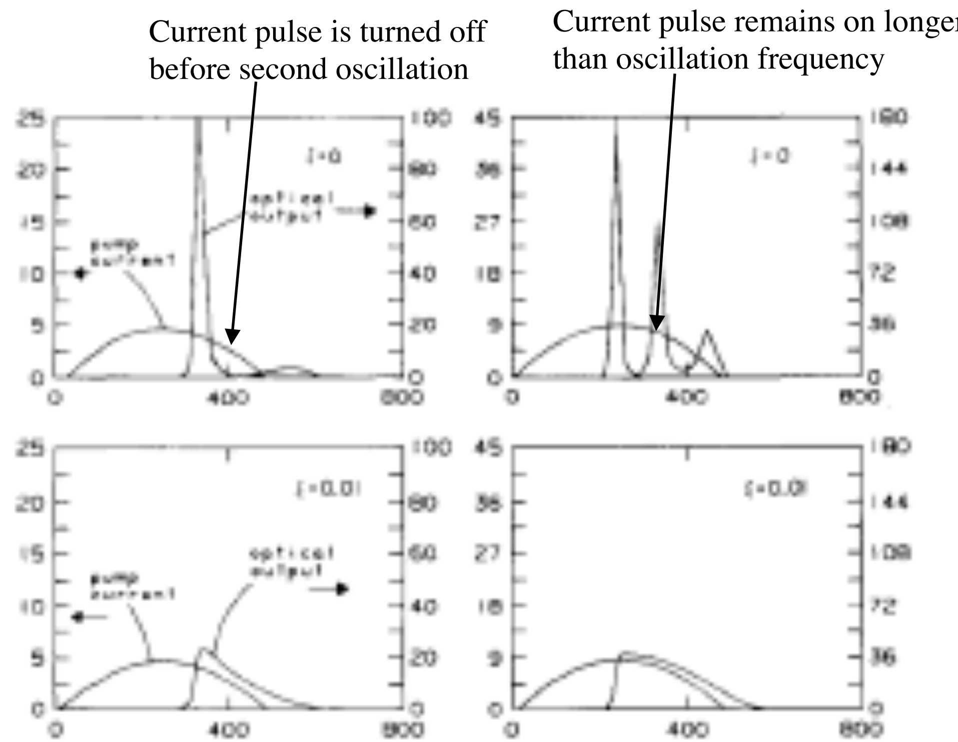
Pulsed Lasers: Motivation

- So far we have studied lasers that emit continuous wave (CW) output power, and studied some aspects of small signal and large signal modulation dynamics.
- In this lecture, we will study a class of laser that emits pulses, or pulse trains, that can be further encoded with data using an external modulator. We will be studying modulators later in the class.
- The following types of lasers that emit pulses are of interest
  - Gain Switched: Directly turning on and off gain of the laser
  - Q-Switched: Periodically increasing the resonator loss (spoiling the Q) with an absorber in the laser cavity
  - Cavity Dumping: Storing photons in the resonator during the off-times and releasing the photons during the on-times.
  - Mode-Locked: Coupling and locking the phases of the cavity modes to each other.
- In this lecture we will talk briefly about gain switched and then concentrate on mode-locked lasers

Gain Switched Lasers

- Pulses are generated by rapidly modulating the laser gain via the injection current (usually with a sinusoid). The output pulse widths can be shorter than if limited by the carrier lifetime.
- Pulses with nanosecond to picosecond durations can be generated.
- The output pulse repetition rate can be adjusted by changing the frequency and bias of the current drive source.

- The laser is turned on from below threshold, and as we saw before with digital modulation, there will be feedback between the photon and carrier density, causing the laser to oscillate at the relaxation oscillation frequency until it is dampened.
- If the applied current pulse is turned off before the second ringing pulse appears, a very short pulse can be generated.
- In the figures at right, ξ is the gain compression factor which plays the role of dampning

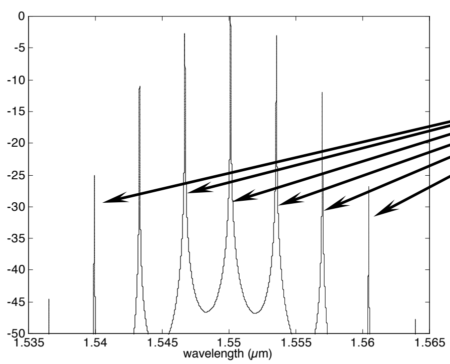


K. Lau, Journal Of Lightwave Technology, Vol. **7.** No. **2.** February **1989**o

Mode-locked Lasers

- Multi-mode lasers emit multiple frequencies that act as independent sources (i.e. the modes are not phase locked with each other). These frequencies are separated (in a FP laser) by the mode spacing $\Delta\nu = c/2nL$. Consider $M = 2S+1$ modes.
- If we use a means to lock the phase of these modes together, then the laser modes at as a single coherent source and we can apply the Fourier Transform to see that the laser will emit a periodic pulse train

Multi-Mode Laser



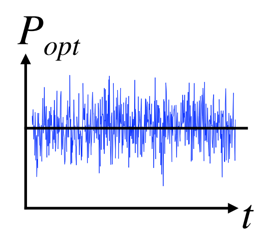
Independent oscillating modes

Mode amplitude

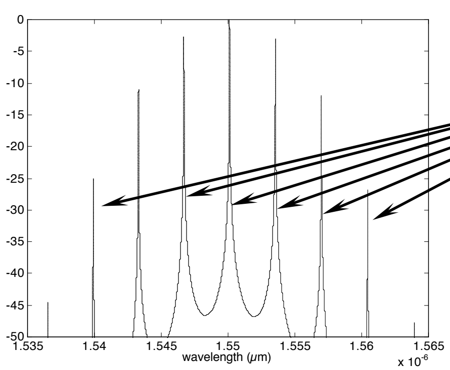
$$E_{out,total} = \sum_{i=-S}^{S} E_i \cos(\omega_i t + \phi_i)$$

Mode frequency

Independent random variable



Mode-Locked Laser



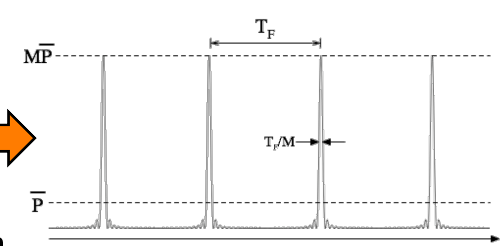
Phase-locked oscillating modes

Mode amplitude

$$E_{out,total} = \sum_{i=-S}^{S} E_i \cos(\omega_i t + \phi)$$

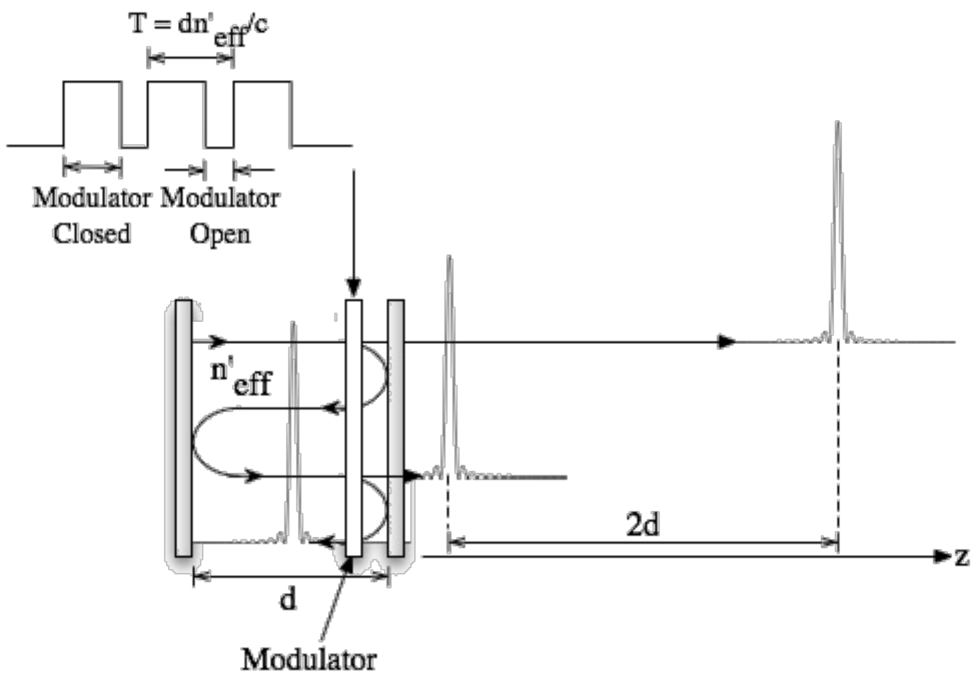
Mode frequency

Fixed phase for each mode



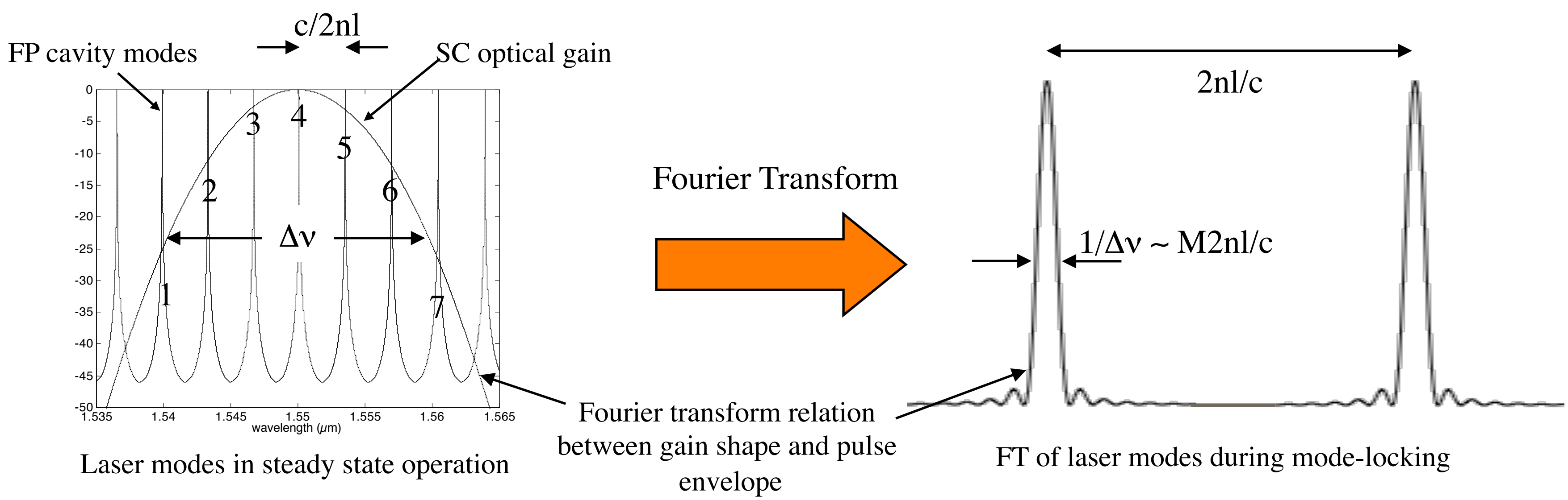
Mode Locked Lasers

- In order to lock the modes together; a loss element that is periodically modulated is placed inside the cavity. The modulater is driven at a frequency that creates a low loss condition only for pulses that match the cavity length.
- The cavity phase relationship will only be reinforced for this set of pulses, and energy that exits the cavity (in the form of these pulses) will be coherent with the cavity round trip time.
- Note that the modulator has to let pulses pass through going both directions in the cavity, hence it runs at twice the rate as the pulses exiting the cavity.



Mode Locked Lasers

- Consider a laser that in steady state (non-modulated) contains M modes. Recall that the spacing between the modes is determined by the resonator (s) and the overall mode shape is determined by the material gain bandwidth as shown below. These can be treated as independent oscillators (incoherent w.r.t. each other).
- Once the modulator is turned on (at a rate equal to the cavity transit time), pulses are emitted from the cavity. The shape of these pulses is determined by the coherent superposition of phase locking the original modes together. Fourier Transform theory tell us the relationship between the frequency and time domain.



Laser modes in steady state operation

FT of laser modes during mode-locking

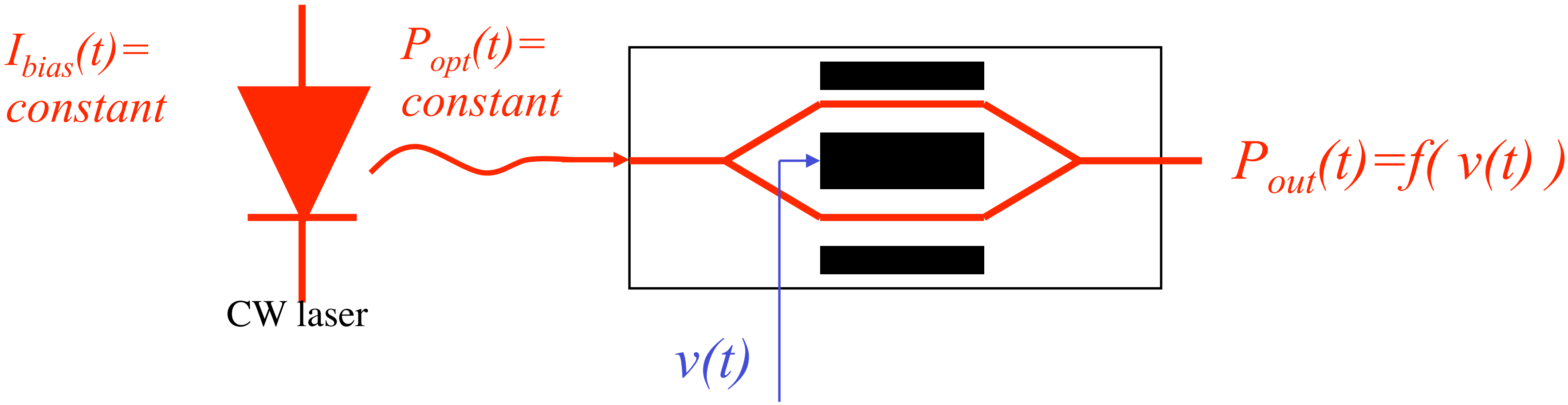
Modulator Basics

- Issues
  - Modulation Bandwidth
  - Modulation Depth
  - Linearity
  - Polarization Independence
  - Insertion Loss
  - Low Switching Voltage and Power Consumption

External Modulators

- All the top-level optical transmission systems are based on external modulation
- External modulators main issues:
  - Modulation Bandwidth
  - Chirp
  - Modulation Depth (extinction ratio)
  - Linearity
  - Polarization Dependence
  - Insertion Loss
  - Low Switching Voltage and Power Consumption

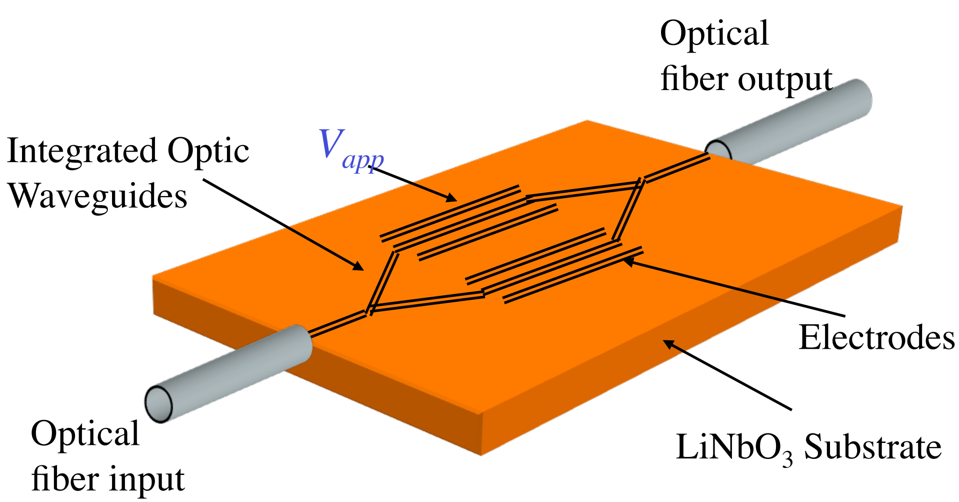
Interferometric Modulators

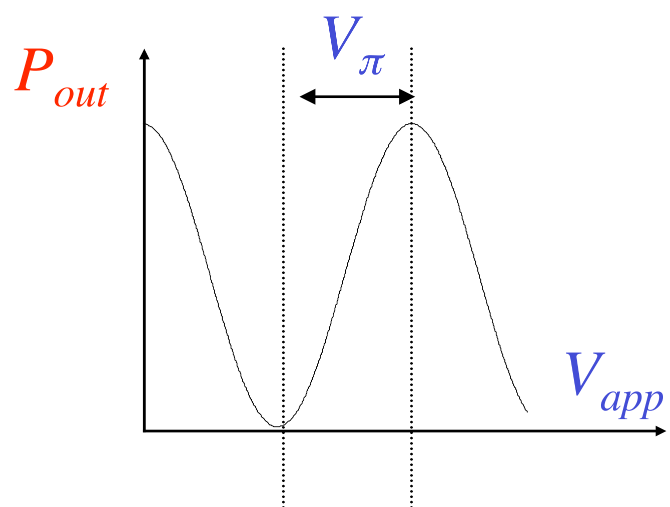


- The laser is operated in CW, so to have a very narrow linewidth
- The output power is a function of the modulator driving signal
- The shape of this function depends on the modulator type
  - Mach-Zehnder modulator on $LiNbO_3$
  - Electro-absorption modulator

Mach-Zehnder Modulator

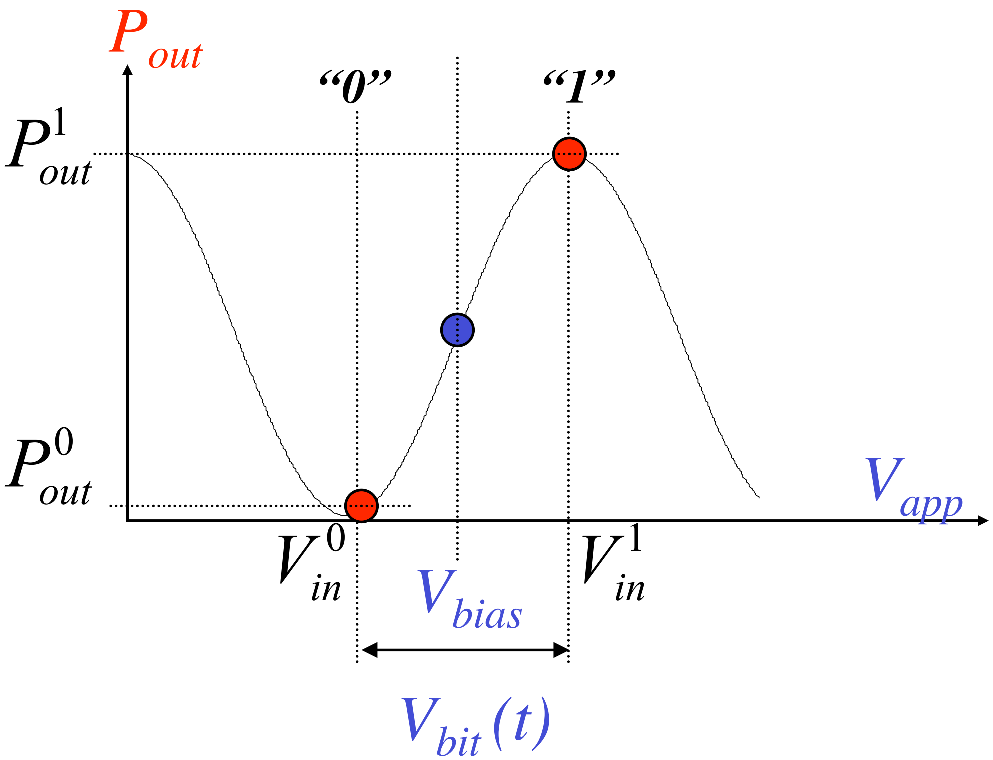
<u>Mach-Zehnder Interferometric (MZI) Modulator</u>





Differential drive of both electrodes decreases V_{π} and allows zero chirp operation.

Digital modulation with MZI



$$V_{amp} = V_{in}^1 - V_{in}^0$$

$$P_{out}^{ave} \cong \frac{P_{out}^1 + P_{out}^0}{2}$$

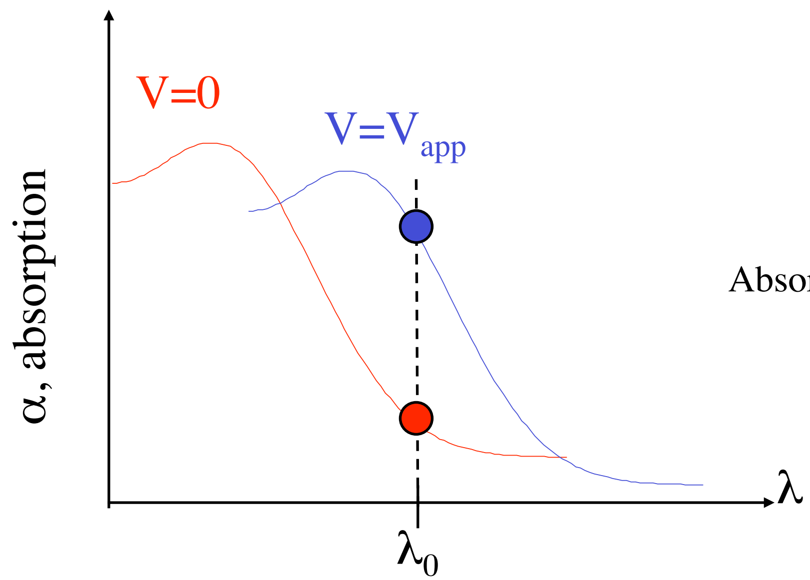
$$\text{Extinction Ratio} = \left.\frac{P_{out}^1}{P_{out}^0}\right|_{dB}$$

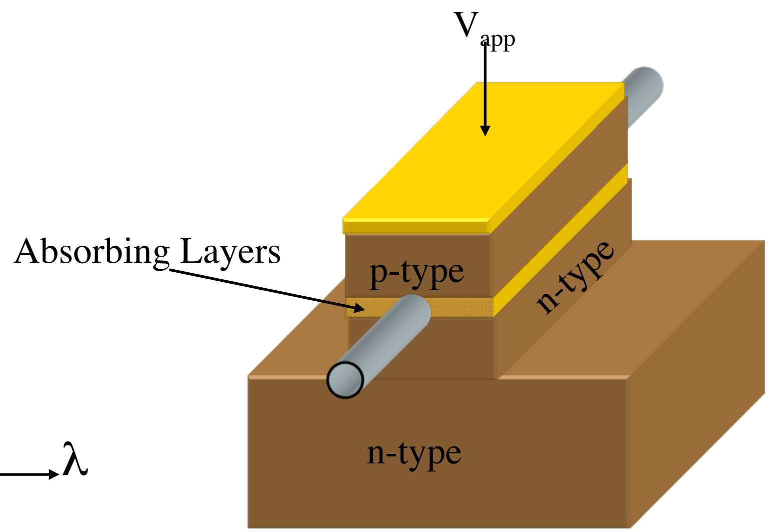
MZI application and characteristics

- MZI on $LiNbO_3$ are the most commonly used external modulators
- The current commercial solutions have the following typical specs:
  - Modulation Bandwidth suitable for 10 Gb/s (and nearly ready for 40 Gb/s)
  - Nearly zero-chirp (or controlled chirp, if requested)
  - Insertion loss: 3-5 dB
  - V_π= 3-5 V
  - Extinction ratio: 15-20 dB
  - Very high polarization dependence (they need a given fixed input polarization for good operation)
    - For this reason, they cannot be used as in-line optical switches
- Together with their electrical drivers, MZI modulators are still quite expensive (4K-7K US$)

Electro-Absorption Modulators (EAMs)

- A semiconductor will absorb light if the input wavelength is below the cutoff wavelength λ_c.
- The cutoff wavelength can be shifted by applying an external voltage to the semiconductor.
- EAMs can be integrated with semiconductor laser sources
- Difficult to make broadband (optical) EAMs due to changing bias for different wavelengths





EAM vs. MZI

- EAMs usually require:
  - Lower voltage swing than external modulators to achieve On-Off modulation
  - They can be (nearly) polarization independent
  - They can be easily integrated with a CW laser on the same chip
    - Much more compact than MZI
    - Less expensive solution
  - It seems that they can easier achieve high modulation bandwidth
- Drawbacks
  - EAMs generate some chirp
    - In this sense, EAMs are much better than laser direct modulation, but worse than MZI