Refractive Index as a function of wavelength

Sellmeier equation

$$n^2 = A + \frac{B}{\lambda^2 - C} - D\lambda^2$$

For GaAs DBR stack Sellmeier coefficients are[1],
A = 10.9
B = 0.97501
C=0.27969
D=0.002467

For $Al_xGa_{1-x}As$ [1],
A = 10.9060 – 2.92x
B = 0.97501
C = (0.52868 – 0.735)2 : x < 0.36
(0.30386-0.105x)2 : x > 0.36
D = 0.002467 (1.41x + 1)

Example

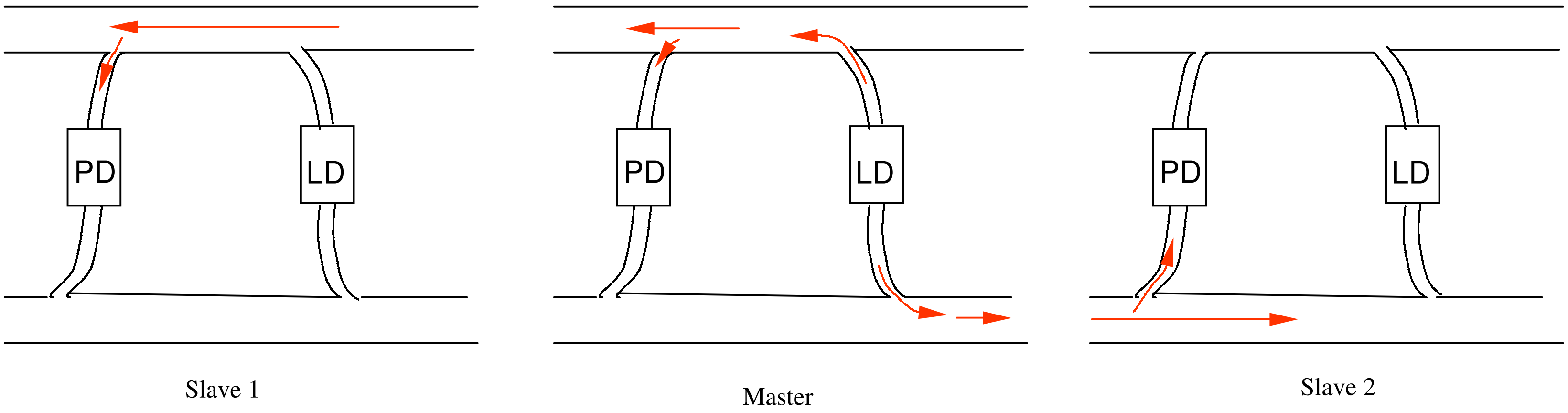
ë= 1.0 ì m

For GaAs

$$n^2 = 10.9 + \frac{0.97501}{\left(1\times10^{-6}\right)^2 - 0.27969} - 0.002467\times\left(1\times10^{-6}\right)^2 = 3.501$$

VCSELs, T.E Sale, p 43

Optical Equivalent for Electronic Bus Logic Design



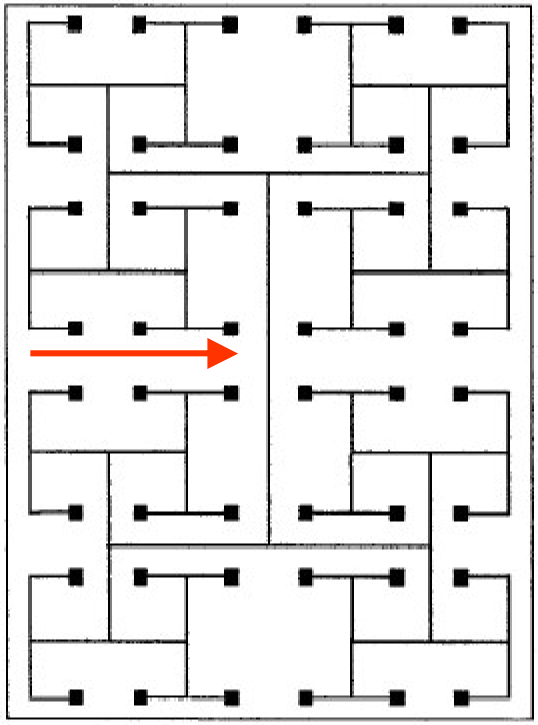
- This scheme is equivalent to an electronic bus line driven by two state open-collector drivers, terminated in pullup resistors
- The state in which no light is present on either waveguide (no LD is operating) corresponds to the unasserted electronic state which is pulled high by the pull up resistors
- The state in which there is light in both waveguides (one or more LD operating) corresponds to the asserted (low-level) electronic line

Optical Equivalent for Tristate Bidirectional Electronic bus line

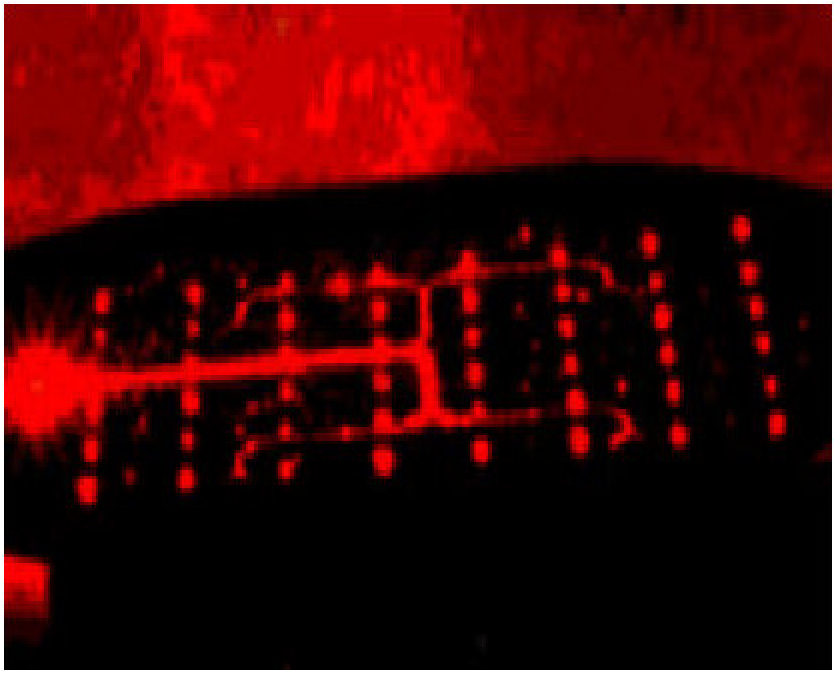
Optical Bus State	**Tri-state Logic State**
Light in Upper Waveguide pair	Asserted High
Light in Lower Waveguide pair	Asserted Low
No Light	High Impedance
Light in Both Pairs	No Equivalent

Optical Clock Signal Distribution

- Clock speed more than 10 times higher than electrical interconnect scheme
- Waveguide splitter and 90 deg bend Waveguide pattern are used to create H-Tree Network
- Optically interconnects a centralized light source to a one-to-many fanouts



H-Tree Optical Network

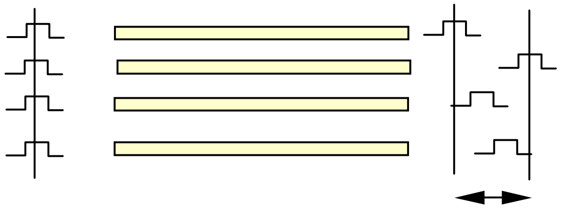


Photograph of the 1-to-48 fanout H-tree on quartz substrate using Ultradel 9120 polyimide.

Optical medium

Skew Time

It is the difference in the propagation time of the signal from channel to channel



Parallel optical fibers

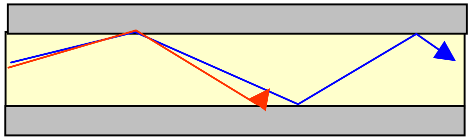
Skew time

Input light pulses

output light pulses
(skewed)

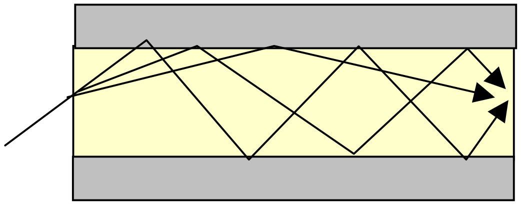
Material Dispersion

Different wavelengths of a light pulse that enter a fiber at one time exit the fiber at different times. Material dispersion is a function of the source spectral width. Material dispersion is less at longer wavelengths. It arises from the variation of the core material as a function of wavelength



Modal Dispersion

Modal dispersion occurs because each mode travels a different distance over the same time span.



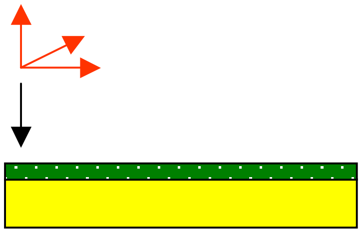
Line Width

Different wavelengths of a light pulse that enter a fiber at one time exit the fiber at different times. Material dispersion is a function of the source spectral width. Material dispersion is less at longer wavelengths. It arises from the variation of the core material as a function of wavelength

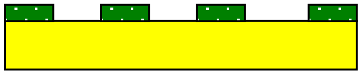
Polymer WaveGuide

Fabrication Steps

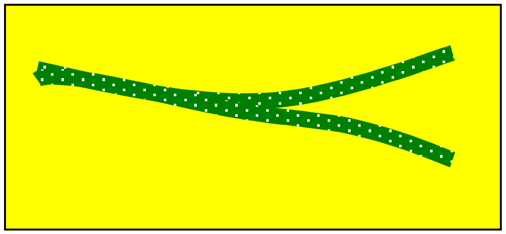
1. Focused HeCd Laser Beam 3-axis Writing (λ=325 nm)



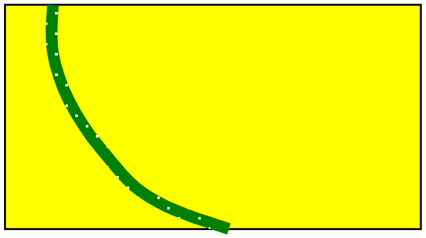
2. After Etching using Organic Solvents and curing



Top View of Some Patterns



1-to-2 3-dB waveguide splitter (Channel width=50µm)

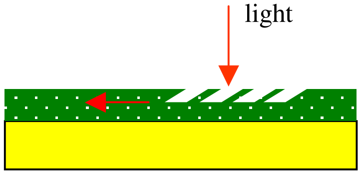


Useful Pattern to direct all fanout beams into single direction at the end of waveguide in an H-tree system
(Curved guide has low loss compared with 90 deg wvaeguide)

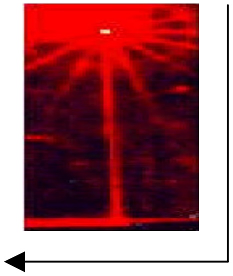
Grating Waveguide Coupler

1. Tilted grating pattern on polyimide waveguide

- Grating pattern on aluminum layer is transferred to polyimide layer using RIE with Faraday Cage

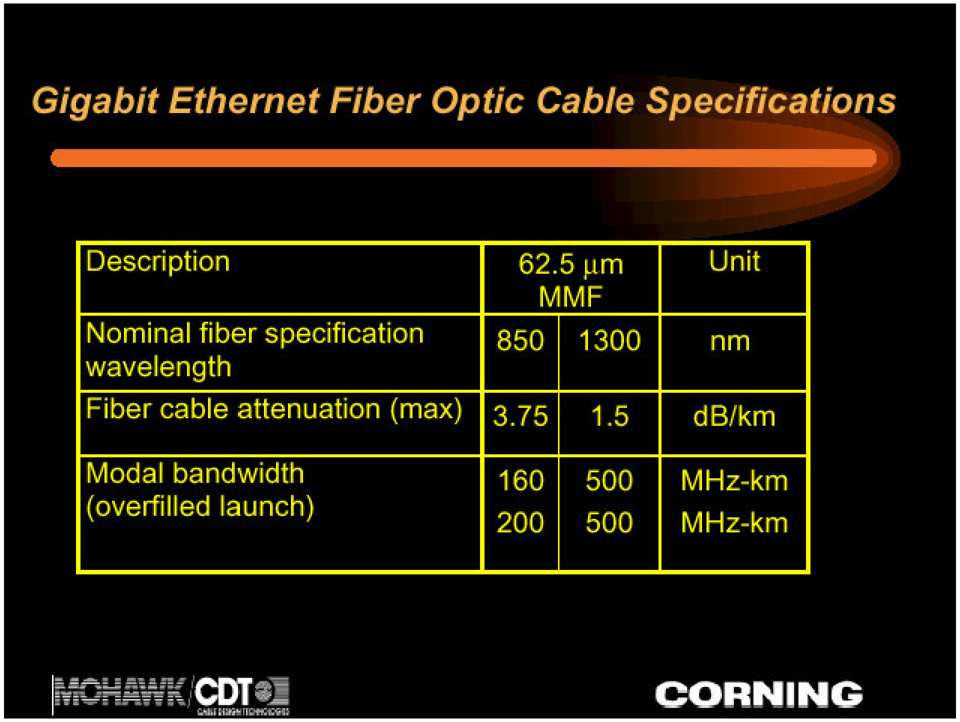


Schematic of Coupling of a surface normal input light into waveguide using tilted grating



Experimental Photograph of Coupling a surface normal input 632.8 nm He-Ne light into the polyimide waveguide

Optical fiber specification[1]



Gigabit Ethernet Fiber Optic Cable Specifications

Description	62.5 µm MMF		Unit
Nominal fiber specification wavelength	850	1300	nm
Fiber cable attenuation (max)	3.75	1.5	dB/km
Modal bandwidth (overfilled launch)	160 200	500 500	MHz-km MHz-km

MOHAWK/CDT

CORNING

fiber core is made up of silicon and germanium (glass) and coated with urethane acrylate polymer[2]

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[1] http://www.mohawk-cdt.com/tech/DesignConsiderationsGigabitNetworks.pdf

[2] .http://www.corning.com/opticalfiber/products__services/msds/frame_msds.asp?BodyURL=/opticalfiber/pdf/ms3496_12-00.pdf

Modal Dispersion

Modal Spread delay [1],

$$\delta t_m = T_{\max} - T_{\min} = \frac{n_1 \Delta L}{c}$$

T_{max}= Travel time of the highest order mode

T_{min} = Travel time of the fundamental mode

n_1 = Refractive index of the core material

n_2 = Refractive index of the clad material

$\Delta = (n_1 – n_2) / n_1$

L – Length of the optical fiber

Modal Dispersion (RMS)[2],

$$\sigma_{\text{mod}} = \frac{\delta t_m}{\sqrt{12}}$$

δt_m = Modal spread delay

Modal Dispersion [3],

$$\sigma_{\text{mod}} = \frac{0.44 \ L^q}{B_{\text{mod}}}$$

B_{mod} = Modal bandwidth of the optical fiber

q = Cutback factor which includes mode coupling and mixing effects

q = 0.5 indicates steady state modal equilibrium is reached

q = 1 indicates less mode mixing

Reasonable estimate is q = 0.7

Example 1 [1],

n_1 = 1.5 for glass

Δ = 0.01

L = 0.1 m

$$\delta t_m = \frac{1.5 \times 0.01 \times 0.1}{3 \times 10^8} = 5 \ ps$$

$$\sigma_{\text{mod}} = \frac{5}{\sqrt{12}} = 1.443 \ ps$$

Example 2 [3,4]

B_{mod} = 160 MHz .Km

q = 0.75

L = 0.1 m

$$\sigma_{\text{mod}} = \frac{0.44 \left(0.1 \times 10^{-3}\right)^{0.75}}{160 \times 10^6} = 2.75 \ ps$$

1. Gerd keiser, Optical fiber communications, second edition, p 107
2. John M. Senior, Optical fiber communications-principles and practice, PHI, p 89
3. Gerd keiser, Optical fiber communications, second edition, p 325
4. Computer Modeling and simulation of the Optoelectronic Technology Consortium (OETC) Optical Bus, whitlock, IEEE Jnl on Selected areas in communications, Vol. 15, No. 4, may 1997

Transfer function of the optical medium

Let us consider multi channel parallel graded index optical fiber as a waveguide between VCSEL array and detector array[1]

Delay time,

$$t_d = (t_{prop} + t_{skew} + \Delta\lambda D)\, L$$

t_{prop}= Propagation delay
t_{skew}= variable delay due to fiber skew
Äë= The difference in laser wavelengths between the channel under consideration and the reference channel
D = Chromatic dispersion
L – Length of the optical fiber

Modal Dispersion,

It is pulse spreading due to multiple light rays traveling different distances and speeds through a fiber.

$$\sigma_{\text{mod}} = \frac{0.44\, L^q}{B_{\text{mod}}}$$

B_{mod} = Modal bandwidth of the optical fiber
q = Cutback factor which includes mode coupling and mixing effects
q =0.5 indicates steady state modal equilibrium is reached
q =1 indicates less mode mixing

Example

Delay time

t_{prop}= 5 ns/m
t_{skew}= 1 ps/m = 1×10^{-3} ns/m
Äë= 0.2 nm
D = 120 ps/km/nm=0.12×10^{-3} ns/m/nm
L = 0.1 m

$$t_d = (5 + 1\times10^{-3} + 0.2\times0.12\times10^{-3})\,0.1$$
$$\approx 0.5\, ns$$

Modal Dispersion

B_{mod} = 160 MHz .Km
q = 0.75
L = 0.1 m

$$\sigma_{\text{mod}} = \frac{0.44\left(0.1\times10^{-3}\right)^{0.75}}{160\times10^{6}}$$
$$= 2.75\ ps$$

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[1] Computer Modeling and simulation of the Optoelectronic Technology Consortium (OETC) Optical Bus, whitlock, IEEE Jnl on Selected areas in communications, Vol. 15, No. 4, may 1997

Transfer function of the optical medium

Material Dispersion

It is dispersion attributable to the wavelength dependence of the refractive index of the material used to form the optical fiber.

$$\sigma_{mat} = \sigma_{src} LD$$

Ó$_{src}$= Linewidth (full width at half maximum) of the source
L= optical fiber length
D = fiber dispersion

Transfer function

$$H_w(f) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(\sigma\pi f)^2} e^{-j2\pi f t_d}$$

where

$$\sigma^2 = \sigma_{mat}^2 + \sigma_{mod}^2$$

3 dB Bandwidth

$$f_{3dB} = \frac{0.1874}{\sigma}$$

Material Dispersion

Ó$_{src}$= 0.5 nm
L= 0.1 m
D = 120 ps/ Km/ nm= 0.12×10^{-3} ns/m/nm

$$\sigma_{mat} = 0.5\times0.1\times0.12\times10^{-3} = 6\times10^{-3}\ ps$$

Transfer function

$$\sigma_{mod} = 2.75\ ps$$

$$\sigma_{mat} = 6\times10^{-3}\ ps$$

$$\sigma^2 = \sigma_{mat}^2 + \sigma_{mod}^2$$

$$\sigma \approx 2.75\ ps$$

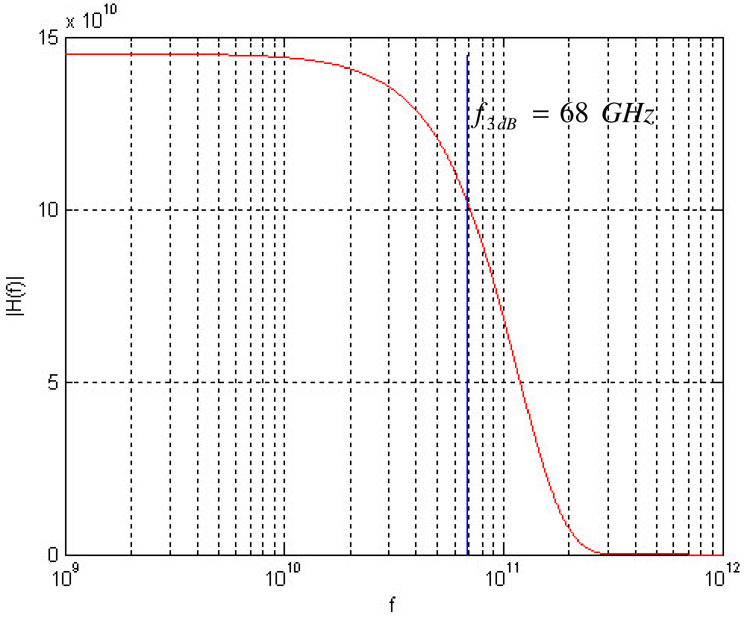
$$f_{3dB} = \frac{0.1874}{2.75\times10^{-12}} = 68\ GHz$$

$$t_d = 0.5\,ns$$

When f= 100 MHz,

$$|H_w| = 1.45\times10^{11}$$

Transfer function of a waveguide (Core – Silica, Clad- Polymer)



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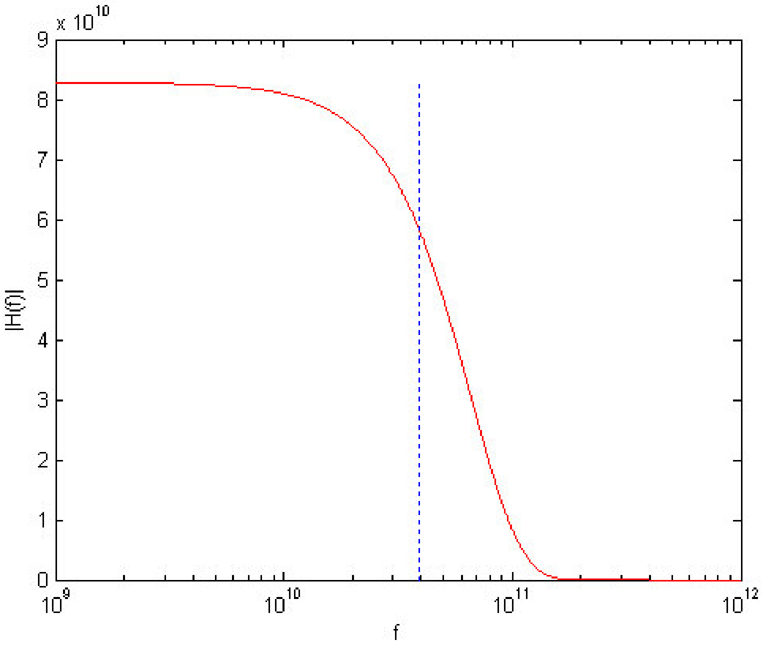
1. Computer Modeling and simulation of the Optoelectronic Technology Consortium (OETC) Optical Bus, whitlock, IEEE Jnl on Selected areas in communications, Vol. 15, No. 4, may 1997

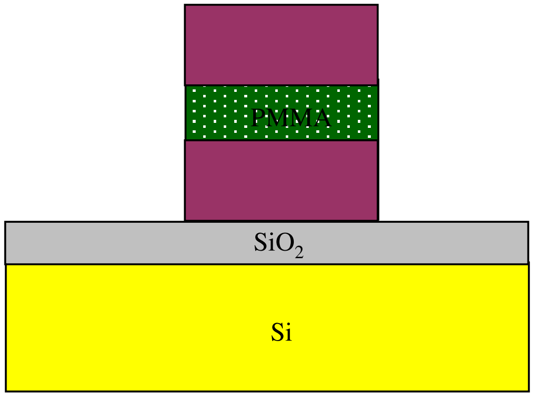
Polymer Waveguide

$B_{mod} = 160$ MHz .Km
$q = 0.75$
$L = 0.1$ m

$$\sigma_{mod} = \frac{0.44\left(0.1\times10^{-3}\right)^{0.75}}{160\times10^{6}} = 2.75\ ps$$



Polymer Waveguide



http://www-hft.ee.tu-berlin.de/polymer/

n_1 = 1.54 for BCB
n_2 = 1.49 for PFCB
Ä = 0.0325
L = 0.1 m

Modal Spread delay,

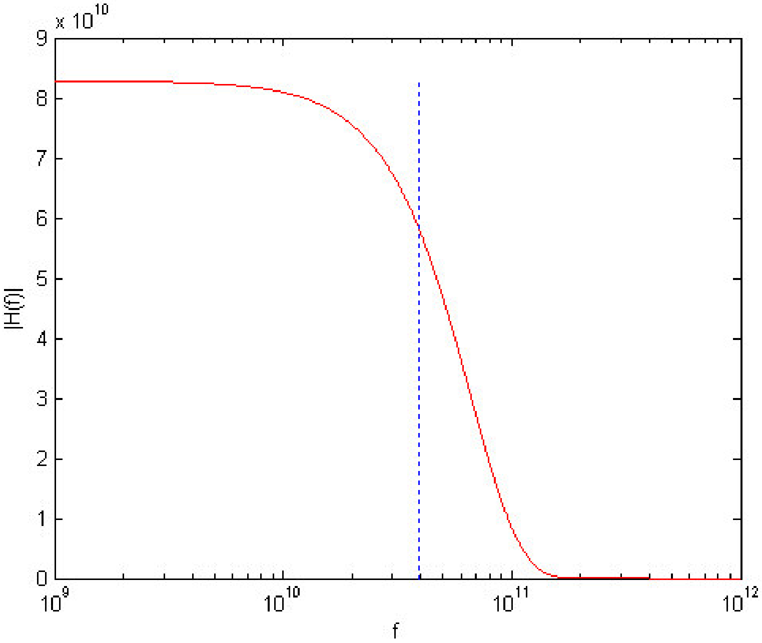
$$\delta t_m = \frac{1.54\times0.0325\times0.1}{3\times10^8} = 16.68\ ps$$

$$\sigma_{\text{mod}} = \frac{16.68}{\sqrt{12}} = 4.816\ ps$$

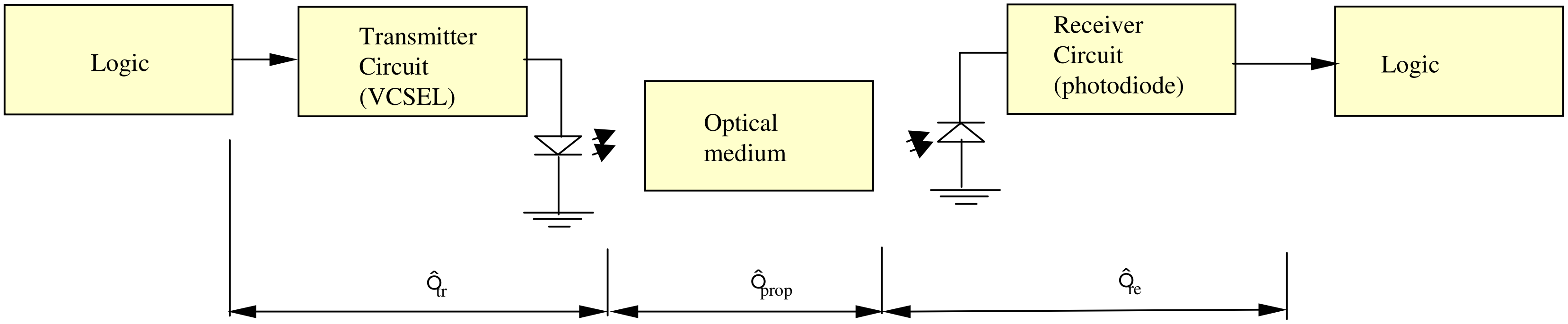
As modal dispersion dominates,

$$f_{3dB} = \frac{0.1874}{4.816\times10^{-12}} = 38.91\ GHz$$

$$t_d = 2.7943\ ps$$



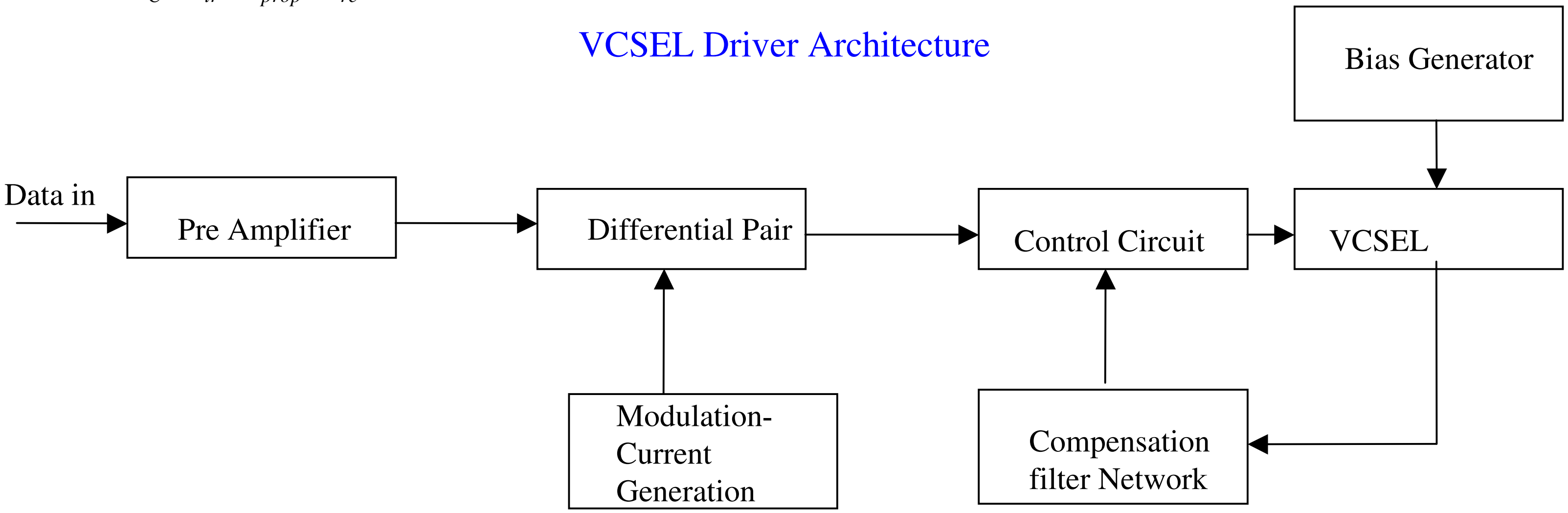
Channel Cycle Time (T_c)



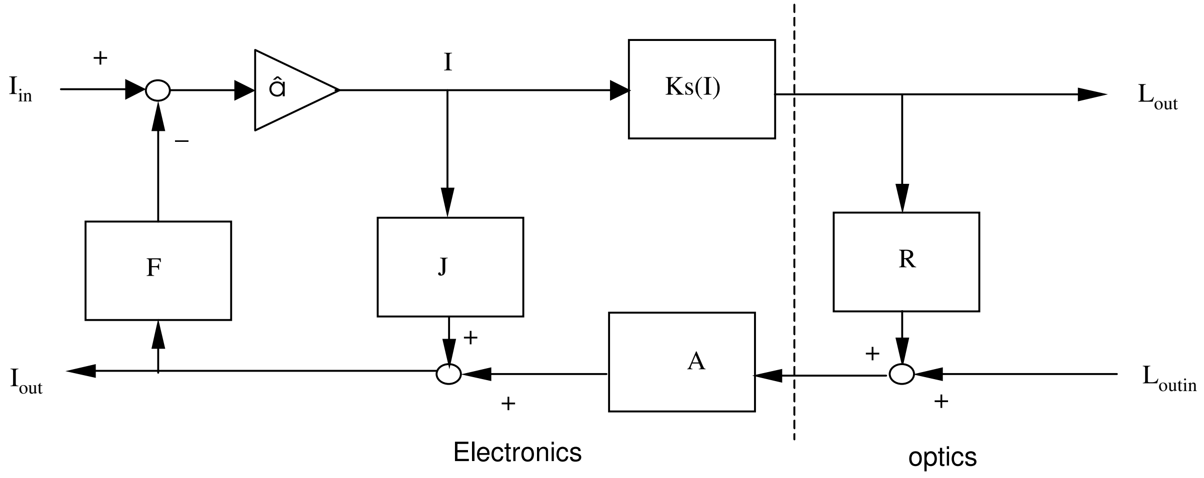
Channel Cycle Time (Tc)

$$T_C = \tau_{tr} + \tau_{prop} + \tau_{re}$$

VCSEL Driver Architecture



Single Pixel Analysis of VCSEL based OEIC



I_{in} – Electronic Input (Current)
I_{out}- Electronic output
I-Output current of VCSEL driver circuit
â-Gain of VCSEL driver circuit
L_{in}- Optical Input (Intensity of the light)
L_{out}- Optical output

Ks(I) – Non linear function to model VCSEL
A- small gain of the photodetector (linear)
R – Optical feedback or cross talk from the source output to the detector input
F – Electronic feedback from the output of the detector to the input of the pixel
J – Current leakage from the source to the detector

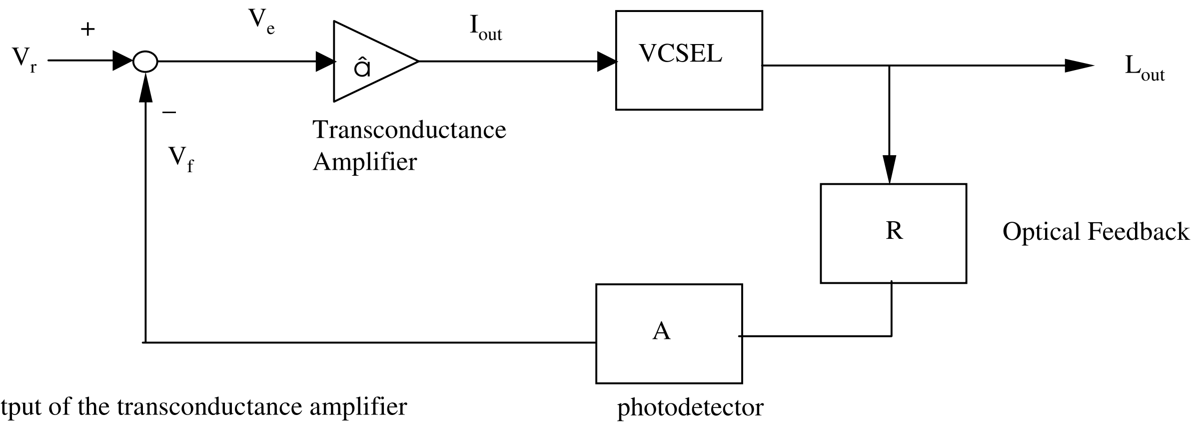
Optical output of VCSEL

$$L_{out} = Ks(I)$$

$$I = \frac{\beta}{1+FJ\beta} I_{in} - \frac{FA\beta}{1+FJ\beta} L_{in} - \frac{FA\beta R}{1+FJ\beta} L_{out}$$

A model for optoelectronically interconnected smart pixel arrays, Azadeh, Jnl. Lightwave Tech..,
Vol. 18, No 10, Oct 2000

Optoelectronic Feedback Loop



I_{out}- Output of the transconductance amplifier
L_{out}- Optical output of the VCSEL
A- small gain of the photodetector (linear)
R – Optical feedback or cross talk from the source output to the detector input

In reality, the gain factors A, â, K are each frequency dependent. For DC analysis, assume that the signals are slowly varying compared to the dominant poles and zeros of the loop

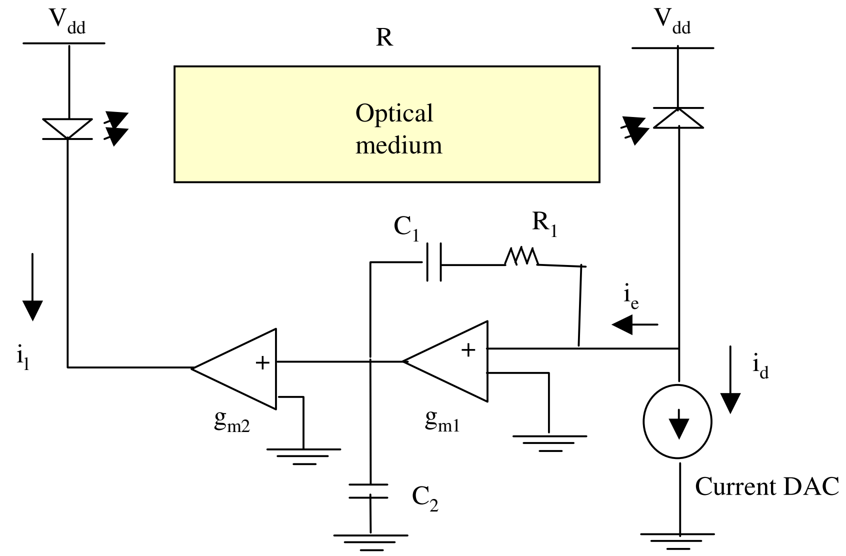
Optical output of VCSEL

$$L_{out} = \begin{cases} 0, & I < I_t \\ K(I - I_{th})^n, & I_t < I < I_{sat} \\ L_{sat}, & I < I_{sat} \end{cases}$$

Where K=gain factor of VCSEL (10 nW/mA^2)
$L_{sat}=K(I-I_{sat})^n$
n is the non ideality factor. For laser diodes, n is 1.

Characteristics of Optoelectronic Feedback for Smart Pixels with Smart Illumination,
Azadeh, 172 IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 5, NO. 2, MARCH/APRIL 1999

Current mode regulation Loop



R – Optical feedback from the laser to the detector input

gm_1, gm_2 are transconductances

I_l is laser current

I_d is DAC current