Homework 5

1. Problem 7.3 in the book
2. Problem 7.6 in the book
3. Find a spec sheet on the web for a Fabry Perot laser diode with wavelength at λ=1310nm.
    a. What is the laser linewidth?
    b. What is the laser power?
4. Find a spec sheet on the web for a DFB laser diode with wavelength at λ=1550nm.
    a. What is the laser linewidth?
    b. What is the laser power?
5. Find a spec sheet for dispersion compensating optical fiber (DCF). What is the length ratio between the DCF and SMF28 for zero total dispersion?
6. If we assume that the fiber attenuation can be fixed with optical amplifiers and dispersion can be fixed with dispersion compensating components, then the link limitation becomes PMD. An optical link is designed to meet the OC-768 standard.
    a. What is the data rate of OC-768?
    b. Using the SMF28 spec sheet, what is the maximum length that this data rate can be transmitted? (Ignore attenuation and chromatic dispersion.)

7.3 In optical communications, signal pulses are often in the shape of a trapezoid, as shown in Figure P7.3.

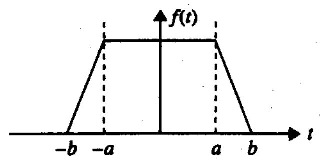


Figure P7.3

(a) Show that the pulse can be written analytically as

$$f(t) = \begin{cases} 1, & 0 < |t| < a \\ \dfrac{b - |t|}{b - a}, & a < |t| < b \\ 0, & \text{elsewhere} \end{cases}$$

(a) at $|t| = b \quad f = \frac{0}{b-a} = 0$

$|t| = a \quad f = \frac{b-a}{b-a} = 1$

(b) Show that the Fourier transform can be written

$$F(\Omega) = a\frac{\sin \Omega a}{\pi \Omega a} + b\frac{\sin \Omega b - \sin \Omega a}{\pi\Omega(b-a)} - \frac{\cos \Omega b - \cos \Omega a + \Omega b \sin \Omega b - \Omega a \sin \Omega a}{\pi\Omega^2(b-a)}$$

$$= \frac{\cos \Omega a - \cos \Omega b}{\pi \Omega^2 (b-a)}$$

(b) $F(\Omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(t)\, e^{-j\Omega t} = \frac{1}{\pi}\int_0^{\infty} f(t) \cos(\Omega t)\, dt$

$= \frac{1}{\pi}\int_0^a \cos(\Omega t)\, dt + \frac{1}{\pi}\int_a^b \left(\frac{b-t}{b-a}\right) \cos(\Omega t)\, dt$

$= \frac{1}{\pi} \frac{\sin \Omega t}{\Omega}\Big|_0^a + \frac{1}{\pi}\int_a^b \frac{b}{b-a} \cos(\Omega t)\, dt - \frac{1}{\pi}\int_a^b \frac{t}{b-a}\cos(\Omega t)\, dt$

$= \frac{1}{\Omega\pi}(\sin a\Omega) + \frac{b}{\pi(b-a)} \frac{\sin \Omega t}{\Omega}\Big|_a^b - \frac{1}{\pi(b-a)\Omega^2}(\cos \Omega t + \Omega t \sin \Omega t)\Big|_a^b$

$= \frac{\sin a\Omega}{\Omega\pi} + \frac{b}{\pi\Omega(b-a)}(\sin(b\Omega) - \sin(a\Omega)) + \frac{1}{\pi\Omega^2(b-a)}(-\cos b\Omega + \cos(a\Omega) - \Omega b \sin \Omega b + \Omega a \sin \Omega a)$

$= \frac{\sin a\Omega}{\Omega\pi} + \frac{1}{\pi\Omega(b-a)}\left[b\sin\Omega b - b \sin \Omega a - \frac{\cos b\Omega}{\Omega} + \frac{\cos a\Omega}{\Omega} - b \sin \Omega b + a \sin \Omega a\right]$

$= \frac{\sin a\Omega}{\Omega\pi} + \frac{1}{\pi\Omega(b-a)}\left[-(b-a)\sin\Omega a - \left(\frac{\cos b\Omega - \cos \Omega a}{\Omega}\right)\right]$

$= \frac{\sin a\Omega}{\Omega\pi} - \frac{\sin \Omega a}{\pi\Omega} - \frac{(\cos b\Omega - \cos a\Omega)}{\pi\Omega^2(b-a)}$

$$\boxed{F(\Omega) = \frac{\cos a\Omega - \cos b\Omega}{\pi\Omega^2(b-a)}}$$

(c) Show that, in the limit when $b = a$, the Fourier transform becomes

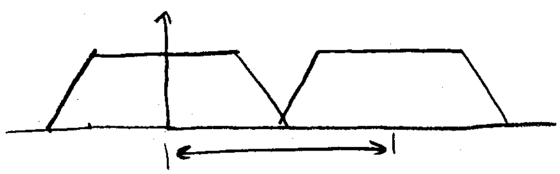
$$F(\Omega) = a\frac{\sin \Omega a}{\pi \Omega a}$$

(c) $\lim_{b \to a} \dfrac{\cos a\Omega - \cos b\Omega}{\pi \Omega^2 (b-a)} = \dfrac{0}{0}$

$\lim_{b \to a} \dfrac{(+\Omega \sin b\Omega)}{\pi \Omega^2} = \dfrac{\sin a\Omega}{\pi \Omega} = \boxed{a \dfrac{\sin a\Omega}{\pi \Omega a}}$

(d) Assume the propagation of a trapezoid pulse with $a = 40$ ps and $b = 60$ ps in a single-mode fiber with $D = 17$ ps/nm-km. Estimate the pulse width at the end of a 100 km fiber. Try to find the pulse shape.

(d) $a = 40\,ps$
$b = 60\,ps$
$D = 17 \frac{ps}{km\ nm}$
$L = 100\,Km$



$B = 8.3$ Gbps

$F(\Omega) = \dfrac{\cos a\Omega - \cos b\Omega}{\pi \Omega^2 (b-a)}$

$\lim_{\Omega \to 0} \dfrac{\cos a\Omega - \cos b\Omega}{\pi \Omega^2 (b-a)} = \dfrac{0}{0}$

$= \lim_{\Omega \to 0} \dfrac{-a \sin a\Omega + b \sin b\Omega}{2\pi \Omega (b-a)} = \dfrac{0}{0}$

$= \lim_{\Omega \to 0} \dfrac{-a^2 \cos a\Omega + b^2 \cos b\Omega}{2\pi (b-a)} = \dfrac{b^2 - a^2}{2\pi (b-a)} = \dfrac{b+a}{2\pi}$

FWHM $\dfrac{\cos a\Omega - \cos b\Omega}{\pi \Omega^2 (b-a)} = \dfrac{b+a}{2\pi}$

FWHM $\Rightarrow \Delta f \approx 12$ GHz $\sim 1.44\,B$

Center region $\Delta f \approx 20$ GHz $\sim 2.4\,B$

$\lambda = -\dfrac{\lambda^2}{c} \Delta f$

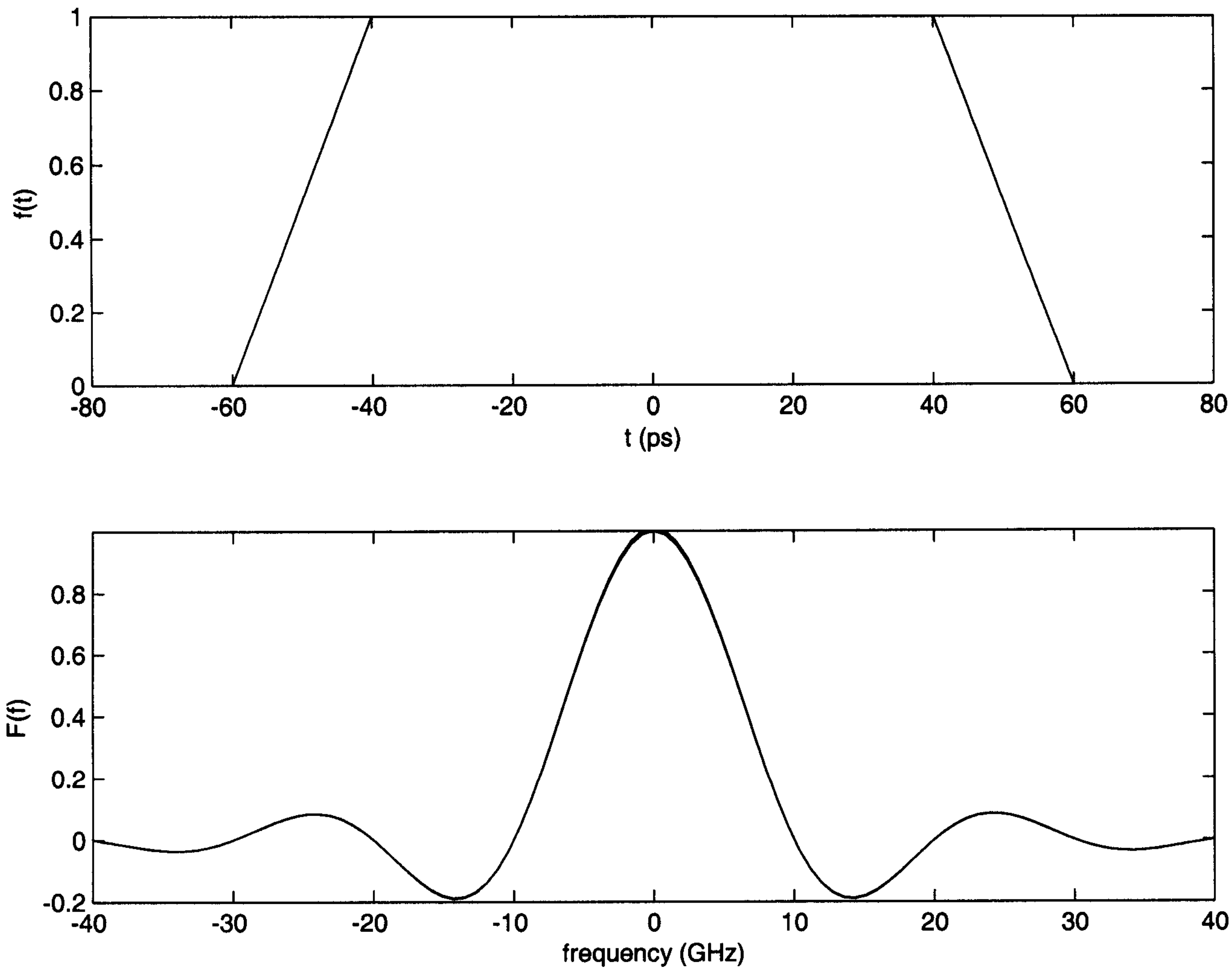
So the pulse spread should be $\Delta T = D \Delta \lambda L$

$= (17 \times 10^{-6}) \dfrac{(1550 \times 10^{-9})^2}{3 \times 10^8} (12 \times 10^9)(100 \times 10^3)$

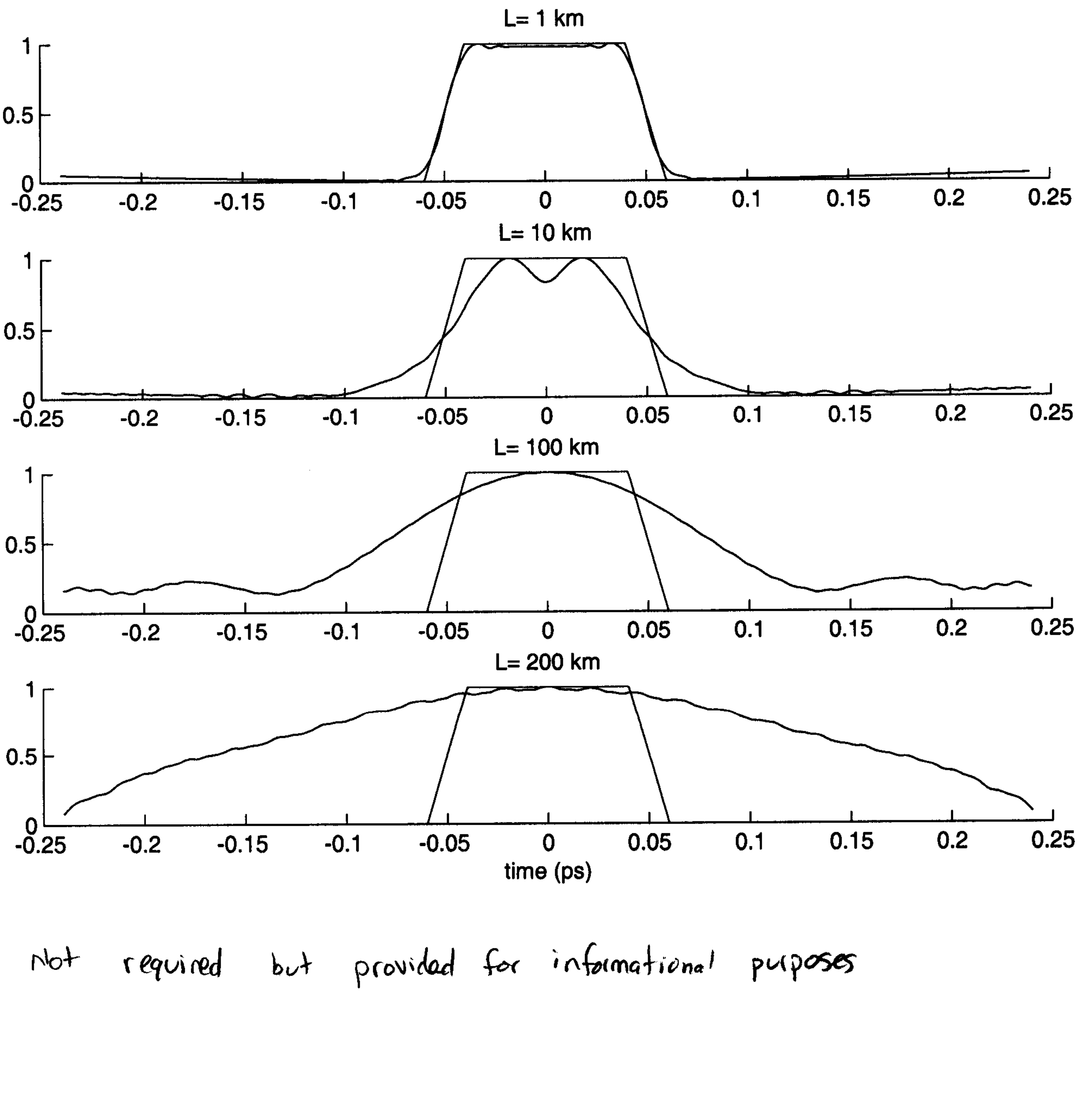
$\Delta T = 0.16$ ns

pulse width $\approx 0.1\,ns + 0.16\,ns = 0.26$ ns

It should also round off



f(t)
1
0.8
0.6
0.4
0.2
0
-80
-60
-40
-20
0
20
40
60
80
t (ps)
F(f)
0.8
0.6
0.4
0.2
0
-0.2
-40
-30
-20
-10
0
10
20
30
40
frequency (GHz)



Not required but provided for informational purposes

7.6 Let n_s and n_f be the indices of refraction for the slow mode and the fast mode, respectively. The PMD is defined as

$$\Delta\tau = \frac{d}{v_{gs}} - \frac{d}{v_{gf}}$$

where v_{gs} and v_{gf} are the group velocities of the modes. Show that

$$\Delta\tau = \left(\frac{d}{c}\Delta n + \frac{\omega d}{c}\frac{\partial \Delta n}{\partial \omega}\right)$$

$$\beta_s = \frac{\omega}{c} n_s$$

$$\frac{1}{v_{gs}} = \frac{\partial \beta_s}{\partial \omega} = \frac{n_s}{c} + \frac{\omega}{c}\frac{\partial n_s}{\partial \omega}$$

$$\frac{1}{v_{gs}} = \frac{1}{c}\left(n_s + \omega \frac{\partial n_s}{\partial \omega}\right)$$

Similar for the fast mode

$$\frac{1}{v_{gf}} = \frac{1}{c}\left(n_f + \omega \frac{\partial n_f}{\partial \omega}\right)$$

$$\Delta\tau = \frac{d}{v_{gs}} - \frac{d}{v_{gf}}$$

$$= \frac{d}{c}\left(n_s + \omega \frac{\partial n_s}{\partial \omega}\right) - \frac{d}{c}\left(n_f + \omega \frac{\partial n_f}{\partial \omega}\right)$$

$$= \frac{d}{c}\left(n_s - n_f + \omega\left[\frac{\partial n_s}{\partial \omega} - \frac{\partial n_f}{\partial \omega}\right]\right)$$

$$\boxed{\Delta\tau = \frac{d}{c}\left(\Delta n + \omega \frac{\partial}{\partial \omega}\Delta n\right)}$$

Demeter Technologies, Inc.

Enabling the Broadband Revolution

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2.5 Gb/s 1310 nm Fabry-Perot Laser Diode

Part No. DTLH101-XXX/DTLH103-XXX

The DTLH101-XXX/DTLH103-XXX is a 1310nm Multi-Quantum Well (MQW) structure InAlGaAs/InP laser diode with a flat window cap. This product is designed for short and medium distance optical fiber communications such as OC-48SR and double speed Fibre Channel. The chip design is optimized for operation at 2.5 Gb/s up to 85 °C.

FEATURES

- 5.6 mm packaging
- Hermetically sealed
- 5 mW CW operation at -40 °C to 85 °C
- High-temperature operation; no TEC required
- PIN photodiode for monitoring laser output
- Cap with ball lens also available

Optical and Electrical Characteristics

PARAMETER	SYMBOL	LIMITS MIN.	TYP.	MAX.	UNIT	CONDITIONS (CW at T_{op} =25 °C unless otherwise specified)
Optical Output Power	P_o	5	-	-	mW	CW
Threshold Current	I_{th}	-	10	13	mA	CW
Slope Efficiency	SE	0.25	0.4	-	mW/mA	P_o = 5 mW, CW
Operating Current	I_{op}	-	-	40	mA	P_o = 5 mW, CW
		-	-	70	mA	P_o = 5 mW, CW, T_{op} = 85 °C
Forward Voltage	V_f	-	1.1	1.6	V	P_o = 5 mW, CW
Lasing Wavelength	λ_c	1290	1310	1330	nm	P_o = 5 mW, CW
Spectral Width (RMS)	$\Delta\lambda$	-	1	2	nm	P_o = 5 mW
Beam Divergence	$\theta_{//}$	-	15	-	degree	P_o = 5 mW, CW, $1/e^2$ power
Beam Divergence	$\theta_{\perp}$	-	40	-	degree	P_o = 5 mW, CW, $1/e^2$ power
Rise Time	t_r	-	-	130	ps	P_o = 5 mW, 20% to 80%
Fall Time	t_f	-	-	130	ps	P_o = 5 mW, 20% to 80%
PD Monitor Current	I_m	50	-	300	µA	P_o = 5 mW, CW
PD Dark Current	I_{dark}	-	-	0.1	µA	$V_{r\,(PD)}$=5 V
PD Capacitance	C	-	8	20	pF	$V_{r\,(PD)}$=5 V, f = 1 MHz

Absolute Maximum Ratings

PARAMETER	SYMBOL	Rating	UNIT
Optical Output Power (CW)	P_o	10	mW
LD Reverse Voltage	V_r	2	V
PD Reverse Voltage	V_r	15	V
PD Forward Current	I_f	1.0	mA
Operating Temperature	T_{op}	°C	-40 to +85
Storage Temperature	T_{stg}	°C	-40 to +100

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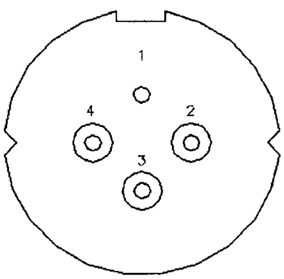
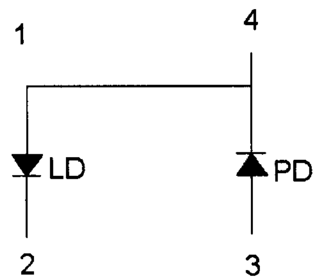
Pinout Details

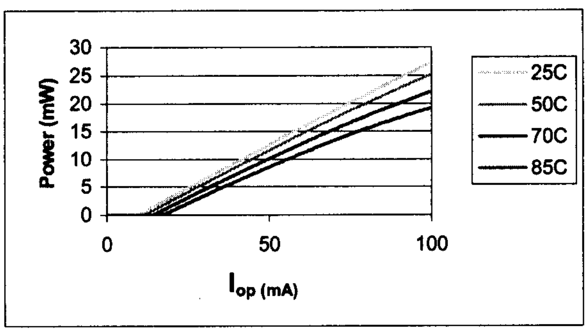
Rear View



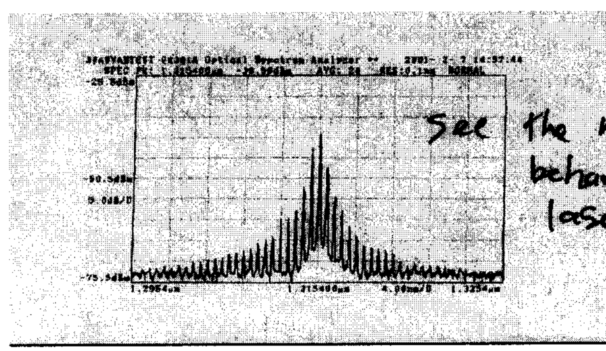


1 = Case (isolated)
2 = Laser diode cathode
3 = Photodiode anode
4 = Photodiode cathode
Laser diode anode

Optical Output Power vs. Forward Current

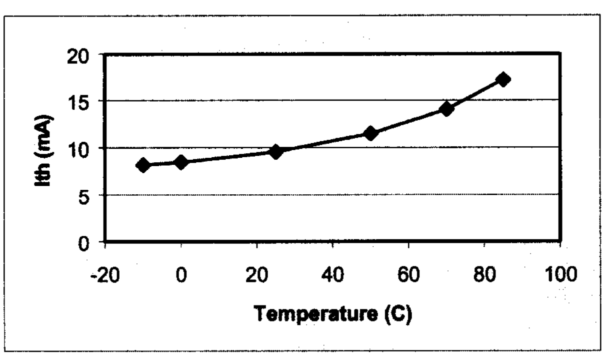


Spectrum

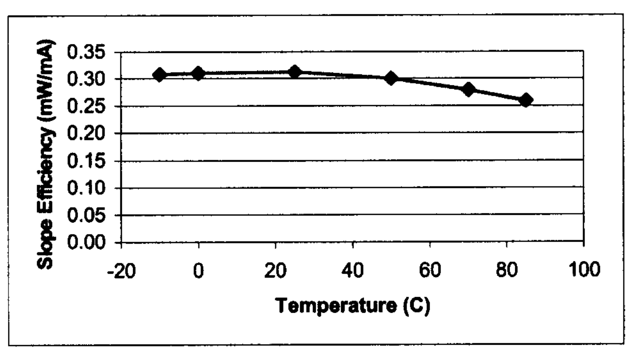


See the multimode behavior of this laser

Threshold Current vs. Temperature



Slope Efficiency vs. Temperature



PowerSource™ 1905 LMI

CW Laser Module with Optical Isolator, Up to 30 mW, C-Band

AVANEX®

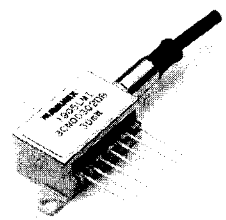
This laser module contains an Avanex SLMQW DFB laser and is designed for use with external modulation optimized for high power Wavelength Division Multiplexed (WDM) systems. The module incorporates a polarization maintaining fiber pigtail, thermoelectric cooler, precision thermistor, and optical isolator for stable operation under all conditions.

FEATURES

- Up to 30 mW Output Power
- Wavelength Selection According to ITU-T G.692 from 1529.55 nm to 1569.59 nm
- 50 GHz Channel Spacing Available
- Optimized for Use with $LiNbO_3$ External Modulator
- Polarization Maintaining Fiber Pigtail
- RIN -140 dB/Hz
- Industry Standard Hermetic 14-Pin Butterfly Package
- InGaAsP Distributed Feedback (DFB) SLMQW Laser

APPLICATIONS

- Ultra Long-Haul 2.5, 10 Gb/s Synchronous Digital Transmission Systems
- WDM Submarine Terminal Digital Transmission Systems
- Instrumentation



OPTICAL CHARACTERISTICS

Table 1, all limits start of life (except I_t, V_t), Tsubmount = 25°C, Tc = 25°C, P_f, V = -5 V, unless otherwise stated.

Parameter	Sym	Conditions	Min	Typ	Max	Unit
Operating Case Temperature	Tc	10 mW & 20 mW 30 mW	-5 -5		70 65	°C °C
Output Power	P_f	Twave = 20 to 35°C	10			mW
			20			mW
			30			mW
Threshold Current	I_{th}				40	mA
Forward Voltage	V_f	P_f, Pin 3 & 11			2.5	V
Laser Forward Current	I_f	10 mW, Pin 3 & 11			100	mA
		20 mW, Pin 3 & 11			190	mA
		30 mW, Pin 3 & 11			260	mA
Emission Wavelength	λ	See Table 3	1529.55		1569.59	nm
Δ (Emitted-Target) Wavelength	Δλ	@Twave, See Table 3 for λ Target	-0.1		+0.1	nm
Submount Temperature	Twave		20		35	°C
Wavelength Drift vs Twave	Δλ/ΔTwave			90		pm/°C
Wavelength Drift vs Tcase	Δλ/Tc			0.2	0.5	pm/°C
Spectral Width	Δλ	CW, P_f, -3 dB		2	5	MHz
TE/TM Extinction Ratio	ER		20			dB
Side Mode Suppression Ratio	SMSR	P_f	40			dB
Relative Intensity Noise	RIN	10 MHz to 10 GHz @ P_f			-140	dB/Hz
Photodiode Current	Im	V = -5 V, @ 10 mW	0.1		1	mA
		V = -5 V, @ 20 mW	0.2		2	mA
		V = -5 V, @ 30 mW	0.3		3	mA
Photodiode Dark Current	Id	V = -5 V			0.1	μA
TEC Current	I_t	See Note 1		0.85	1.3	A
TEC Voltage	V_t	See Note 1		1.6	2.5	V
Thermistor Resistance	R_{th}		9.7		10.3	kΩ
Thermistor β Constant	β		3800	3900	4000	K

Note 1: Tcase = 70°C (10 and 20 mW), Tcase = 65°C (30 mW), Tsubmount = 20°C, @1.2 x P_f

POWERED by AVANEX

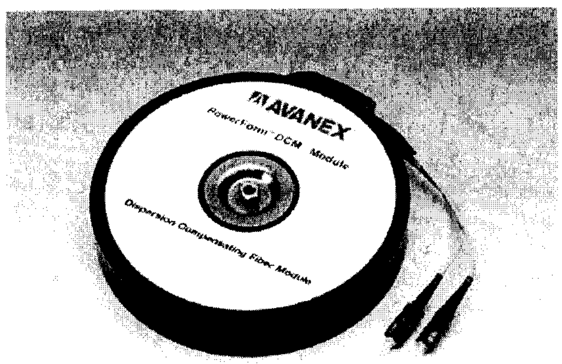
D2305

PowerForm™
DCM® Modules for Single-Mode Fiber, C-Band

AVANEX®

100% Dispersion and Dispersion Slope Compensation

Based on negative dispersion compensation fiber technology, these field-proven standard SMF DCM® modules work hand-in-glove with standard single-mode fibers. Specifically, they complement the transmission characteristics of SMF-28™ fiber and other standard single-mode fibers. PowerForm™ DCM® Modules efficiently counteract the effects of chromatic dispersion across the C-Band wavelengths by providing 100 percent dispersion slope compensation. Standard modules are available with 1545 nm center wavelength, and dispersion values from –50 to –2100 ps/nm increments. Other center wavelength and dispersion values are available upon request. Packaging includes stand-alone module and network-ready rack versions.



FEATURES

- Provides Optimized Dispersion Compensation Across the 1525 nm to 1565 nm Passband on Single-Mode Fiber (ITU G.652)
- Low Insertion Loss and Polarization Mode Dispersion
- Enhances DWDM System Performance by Reducing Accumulated Residual Dispersion
- Discrete Module or 1RU End User Ready Packaging Options
- Multiple Connector Types Available
- End-User Ready Rack Packaging Holds Two Standard Length Modules or One Extended Length SMF DCM® Module

APPLICATIONS

- ITU G.652 Fiber Compensation
- Long-Haul and Ultra Long-Haul Communications Systems with Conventional Single-Mode Fiber, Operating in the 1525 nm to 1565 nm Wavelength Range
- High Bit-Rate DWDM Systems
- Longer Reach Metropolitan Networks
- 10 Gb/s Ethernet Designs
- Cable Television Video Links
- Dispersion Fine-Tuning

DEFINITION OF DISPERSION SLOPE COMPENSATION

To efficiently manage the dispersion and the dispersion slope of a transmission fiber, the dispersion compensating fiber should satisfy the following equation:

$$SC = \frac{K_{NDSF}^{1545}}{K_{DCF}^{1545}} = \frac{\left(D_{NDSF}^{1545} \big/ S_{NDSF}^{1545} \right)}{\left(D_{DCF}^{1545} \big/ S_{DCF}^{1545} \right)} = 1$$

S_{NDSF}^{1545}: Dispersion slope of conventional single-mode fiber @ 1545 nm.

D_{NDSF}^{1545}: Dispersion of conventional single-mode fiber @ 1545 nm.

SMF fiber Typical Value of K_{NDSF}^{1545} equals 275 nm.

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PowerForm™
DCM® Modules for Single-Mode Fiber, C-Band

AVANEX®

KEY OPTICAL PARAMETERS FOR COMMON MODULE LENGTHS

Module Description[1]	Measured Dispersion[2] (ps/nm) @ 1525 nm Min	@ 1525 nm Max	@ 1545 nm Min	@ 1545 nm Max	@ 1565 nm Min	@ 1565 nm Max
DCM-10-SMF-C	-159	-145	-170	-158	-184	-168
DCM-20-SMF-C	-315	-293	-337	-319	-364	-340
DCM-40-SMF-C	-629	-588	-673	-640	-727	-682
DCM-60-SMF-C	-942	-883	-1009	-960	-1090	-1024
DCM-80-SMF-C	-1251	-1183	-1340	-1286	-1448	-1371
DCM-100-SMF-C	-1560	-1482	-1671	-1611	-1805	-1718

Note 1: Numbers represent typical spans of conventional single-mode fiber in kilometers.
Note 2: Dispersion is over temperature (-5°C to 70°C).

longer length ↓

at $\lambda = 1545$

$D_{intra} = \frac{0.092}{4}\left[1545 - \frac{1310^4}{1550^3}\right] = 17.2 \frac{ps}{km \cdot nm}$

$\left(17.2 \frac{ps}{km \cdot nm}\right)(L) = D$

$L = \frac{D}{17.2}$

SPECTRAL CHARACTERISTICS

Module Description[1]	1545 Kappa K $_{DCF}$ (nm)	Insertion Loss[2] (dB) Typ	Insertion Loss[2] (dB) Max	Polarization Mode Dispersion[3] (ps) Typ	Polarization Mode Dispersion[3] (ps) Max
DCM-10-SMF-C	275 ± 10%	1.2	2.1	0.1	0.3
DCM-20-SMF-C	275 ± 10%	1.8	2.7	0.2	0.4
DCM-40-SMF-C	275 ± 10%	3.2	4.1	0.2	0.5
DCM-60-SMF-C	275 ± 10%	4.5	5.5	0.2	0.6
DCM-80-SMF-C	275 ± 10%	6.0	6.9	0.3	0.7
DCM-100-SMF-C	275 ± 10%	7.4	8.4	0.3	0.8

Note 1. Numbers represent typical spans of conventional single-mode fiber in kilometers.
Note 2. This is the maximum optical loss incurred, end-of-life, over temperature, over wavelength range, and polarization including one pair of connectors.
Note 3. Linear mean differential group delay over wavelength range 1510 – 1570 nm, 1 nm step, using the Jones Matrix method at room temperature.

longer lengths have higher insertion loss and more PMD

length of SMF28 at $\lambda = 1545$nm (km)

	Min	Max
DCM-10	9.9	9.2
DCM-20	19.6	18.6
DCM-40	39.1	37.2
DCM-60	58.7	55.8
DCM-80	77.9	74.8
DCM-100	97.2	93.7

6. If we assume that the fiber attenuation can be fixed with optical amplifiers and dispersion can be fixed with dispersion compensating components, then the link limitation becomes PMD. An optical link is designed to meet the OC-768 standard.
   a. What is the data rate of OC-768?
   b. Using the SMF28 spec sheet, what is the maximum length that this data rate can be transmitted? (Ignore attenuation and chromatic dispersion.)

(a) look up on google

OC-768 is the data rate

$(768)(51.85\times10^{6})$

$B = 39.82$ Gbps

$B \approx 40$ Gbps

$$\left(0.2\,\frac{ps}{\sqrt{Km}}\right)\left(\sqrt{L}\right) = \frac{1}{4B}$$

$$(0.2\times10^{-12})(\sqrt{L}) = \frac{1}{(4)(40\times10^{9})}$$

$$L = \left(\frac{1}{(160\times10^{9})(.2\times10^{-12})}\right)^{2}$$

L = 976.6 Km