Lasers and detectors for SmallSat Optical Communications

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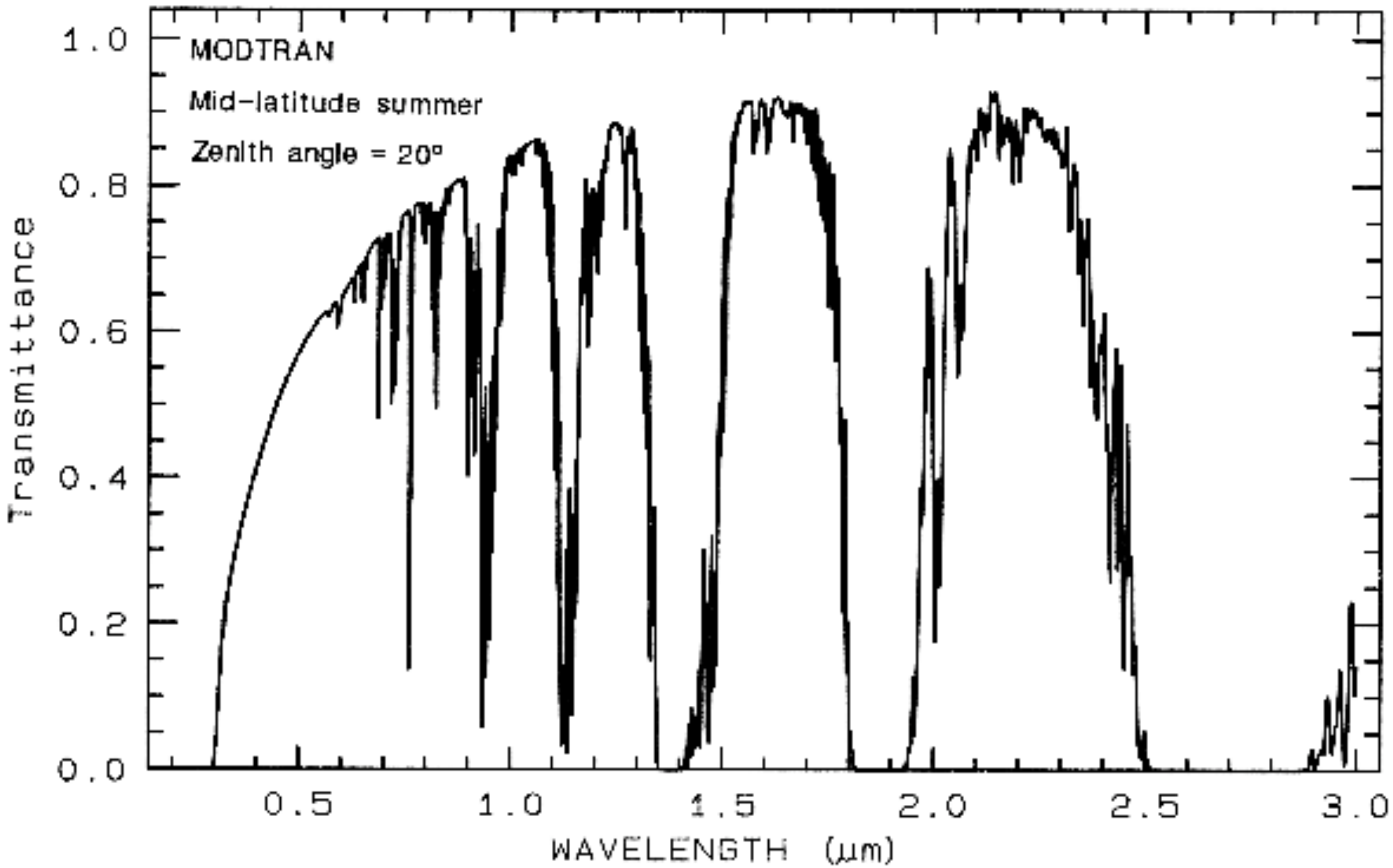
NASA Goddard Space Flight Center

July 13, 2016

What wavelength?

- Optimizing? Cost? Performance?
- Laser wavelength availability
- Optical amplifier wavelength availability
- Type of receiver: Direct? Photon count? Coherent?
- Atmospheric transmission

Atmospheric transmission



Laser Transmitters
Modulation format

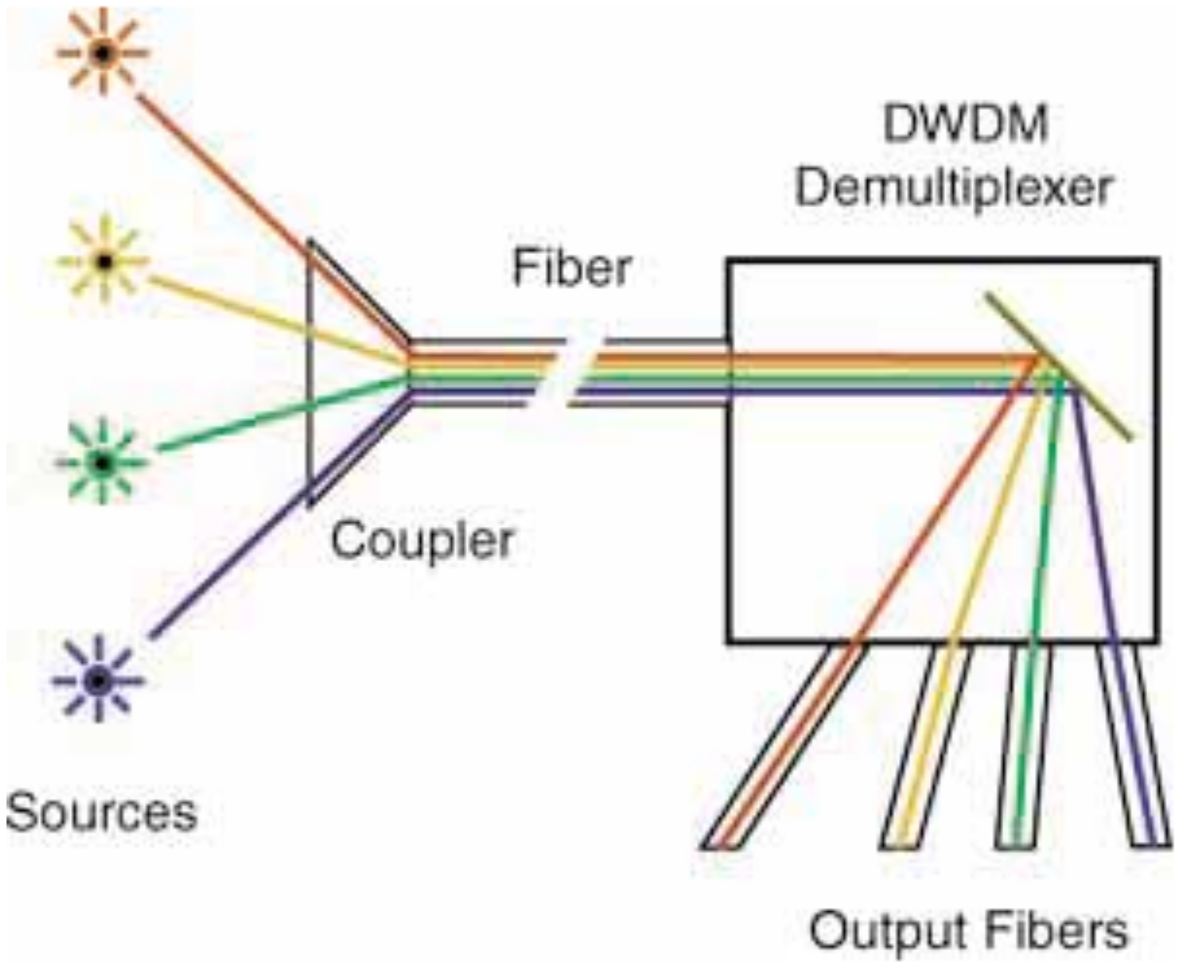
Direct detection system:

On-Off Keying (OOK), Pulse Position Modulation (PPM)

Coherent detection system:

Phase-Shift-Keying (PSK), Frequency-Shift-Keying (FSK)

Wavelength Division Multiplexing (WDM)



Laser transmitters
Modulation implementation

Direct detection system:

- Direct modulation (current=> intensity)
  Simple, low cost, may increase optical spectral width

- External modulator
  Extra electro-optic component and
  higher power drive electronics.
  Can buy integrated laser + modulator
  Gives narrower optical spectral width

Laser transmitters
Modulation implementation

Coherent detection system:

- External modulator
  Extra electro-optic component and
  higher power drive electronics.
  Can buy integrated laser + modulator
  Gives narrower optical spectral width

Examples

Example – direct modulation

850 nm Vertical Cavity Surface Emitting Laser (VCSEL) (4 x 28G)

FINISAR

Optical Transceivers

100GBASE-SR4 and OT

FTLC9141SENM

Distance:	100 m
Data Rate (max):	112 Gb/s
Protocol:	OTN OTU4 Compliant, 100G Ethernet Compliant
Low End Case Temperature (°C):	-5
High End Case Temperature (°C):	75
Diagnostics:	Digital
Transmitter:	4x VCSEL Array
Receiver:	PIN
Voltage Supply:	3.3
Connector:	MPO (MTP12)
Wavelength:	850nm Band

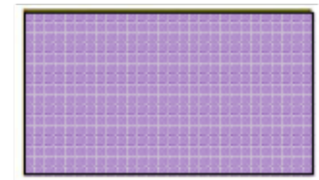
Digi-key Inc. price: $ 1551.68

Even higher single VCSEL rate: 40 Gbps (8 ps rise/fall) 850 nm transmitter Oscillator

Up to 40 Gbit/s 850nm VCSEL Transmitter Optical Subassembly (TOSA)

40 Gbit/s VCSEL driver

Product Code: A40-150C80



All product specifications and descriptions are subject to change without notice.

www.v-i-systems.com **VI Systems GmbH** Hardenbergstrasse 7 D-10623 Berlin

Parameter VCSEL	Symbol	Test Condition	Min	Typ	Max	Unit
Peak emission wavelength	λ	P_{out} = 0.5mW	840	850	860	nm
Case operating temperature	T_{op}		-10		85	°C
RMS spectral width	$\Delta\lambda$	P_{out} = 0.5mW			0.4	nm
λ_p temperature coefficent	$\Delta\lambda_p$			0.06		nm/°C
Relative intensity noise	RIN	40 Gbit/s			130	dB/Hz
Rise/Fall time	T_r	P_{out} = 0.5mW		8		psec
	T_f	40 Gbit/s		9		psec
		20-80%				
Threshold current	I_{th}			0.7		mA
I_{th} temp variation	ΔI_{th}	T = -10 °C to 85 °C		+1 .0	+2.0	mA
Laser forward voltage	V_f	P_{out} = 0.5mW		2.2		V

Example: 1550 nm transceiver

- 10Gb/s,
  Single Mode,
  Multi-Rate SFP
  + Transceiver

Digi-key Inc. price: $ 870.03

Transmitter front-end PIC
DFB with Integrated MZ modulator
Comparison of integrated InP to LiNbO3

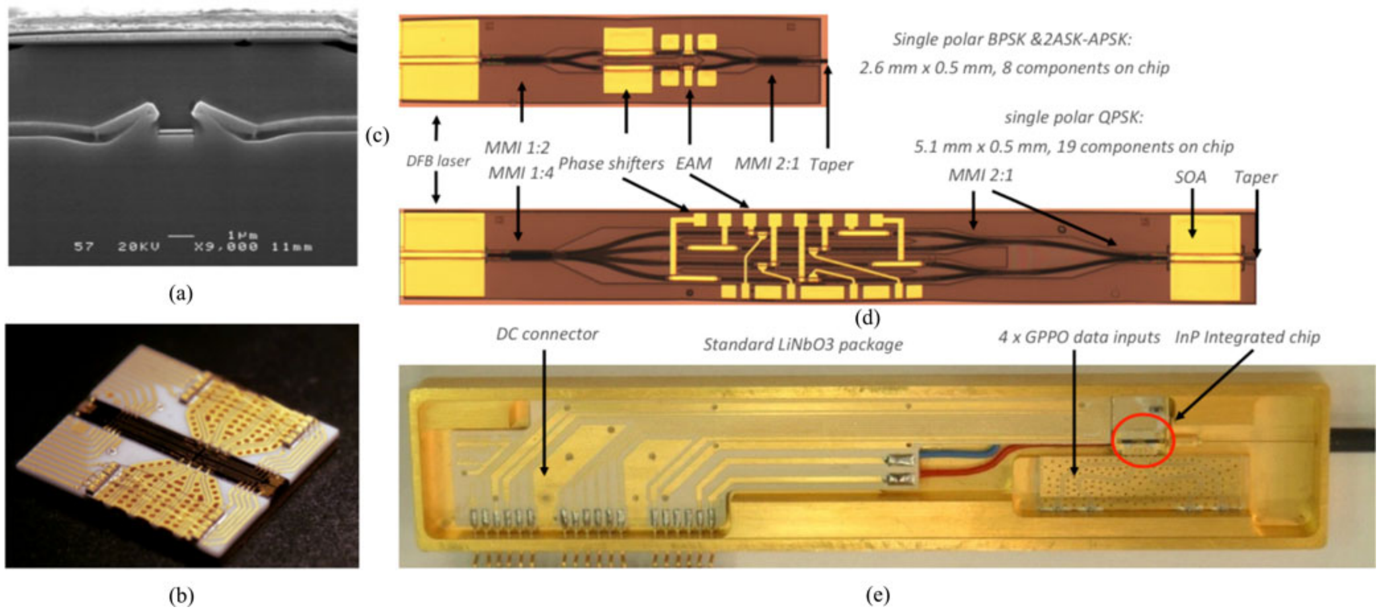


Fig. 2. (a) A cross-view of a SI buried ridge. (b) Transmitter chip mounted on HF submount. Photographies of integrated (c) BPSK & 2ASK-2PSK transmitter,

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 33, NO. 3, FEBRUARY 1, 2015 663

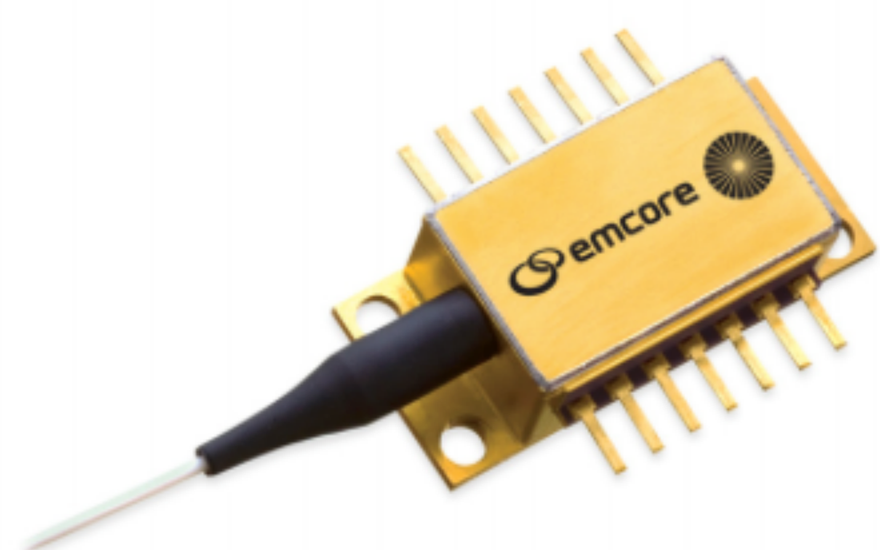
Monolithic Integrated InP Transmitters Using Switching of Prefixed Optical Phases

Guilhem de Valicourt, Haik Mardoyan, M. A. Mestre, P. Jennevé, J. C. Antona, S. Bigo, O. Bertran-Pardo, Christophe Kazmierski, J. Decobert, N. Chimot, and F. Blache

Distributed Feedback (DFB) laser
(i.e. includes grating to give narrow optical spectra)

1751A 1550 nm DWDM DFB Laser Module

emcore
empower with light



400G modulator

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DWDM Transmission

- Linecards and Subsystems ›
- Transponder Modules and Transceivers ›
- Components ›

Client Side/Datacom

- Modules and Transceivers ›
- Transponder and Transceivers Components ›

Products > DWDM Transmission > Components > 400G Modulators > 400G Lithium Niobate Modulator

400G Lithium Niobate Modulator

Request Info

Description | Applications | Features | Related Products

DESCRIPTION

The Oclaro 400G Lithium Niobate external modulator is explicitly designed to enable 400G and beyond speeds on a single wavelength or carrier. This modulator is a high electro-optic bandwidth Polarization Multiplexed Quad Parallel Mach-Zehnder (PM-QMZ) that integrates into a hermetic package an input beam splitter, four parallel Mach-Zehnder modulators configured for I-Q modulation, a polarization combiner, and monitor photodiodes for power and bias control.

Optical amplifiers

- Fiber optic amplifiers:
  - Erbium doped: 1530 -1570 nm range
  - Ytterbium doped: 1030 -1080 nm range

- Semiconductor tapered amplifiers
  - 625 – 1500 nm range

5 W fiber amp

37dBm Multiport High Power Fiber Amplifier Module

Description

YEDFA-MP series of high power fiber amplifiers are especially designed for FTTx, CATV, FDC and HFC analog amplification applications those require high reliability. Compared to conventional amplifiers, these modules are more compact, powerful, stable and reliable.

This line of high power fiber amplifier features a dual stage amplification configuration, pre-amplifier and power amplifier and the use of selected multi-channel splitters with extremely low IL and high reliability.

Both input and output signals are sampled and monitored with a feedback circuit. ACC (automatic current control) and APC (automatic power control) circuits are designed into the amplifier to ensure high stability and reliability of output power. Standard user-friendly RS-232 interface enables reliable connectivity with customer's control system.

Yb amplifier module
(just slightly too big for CUBESat)

MINTECH

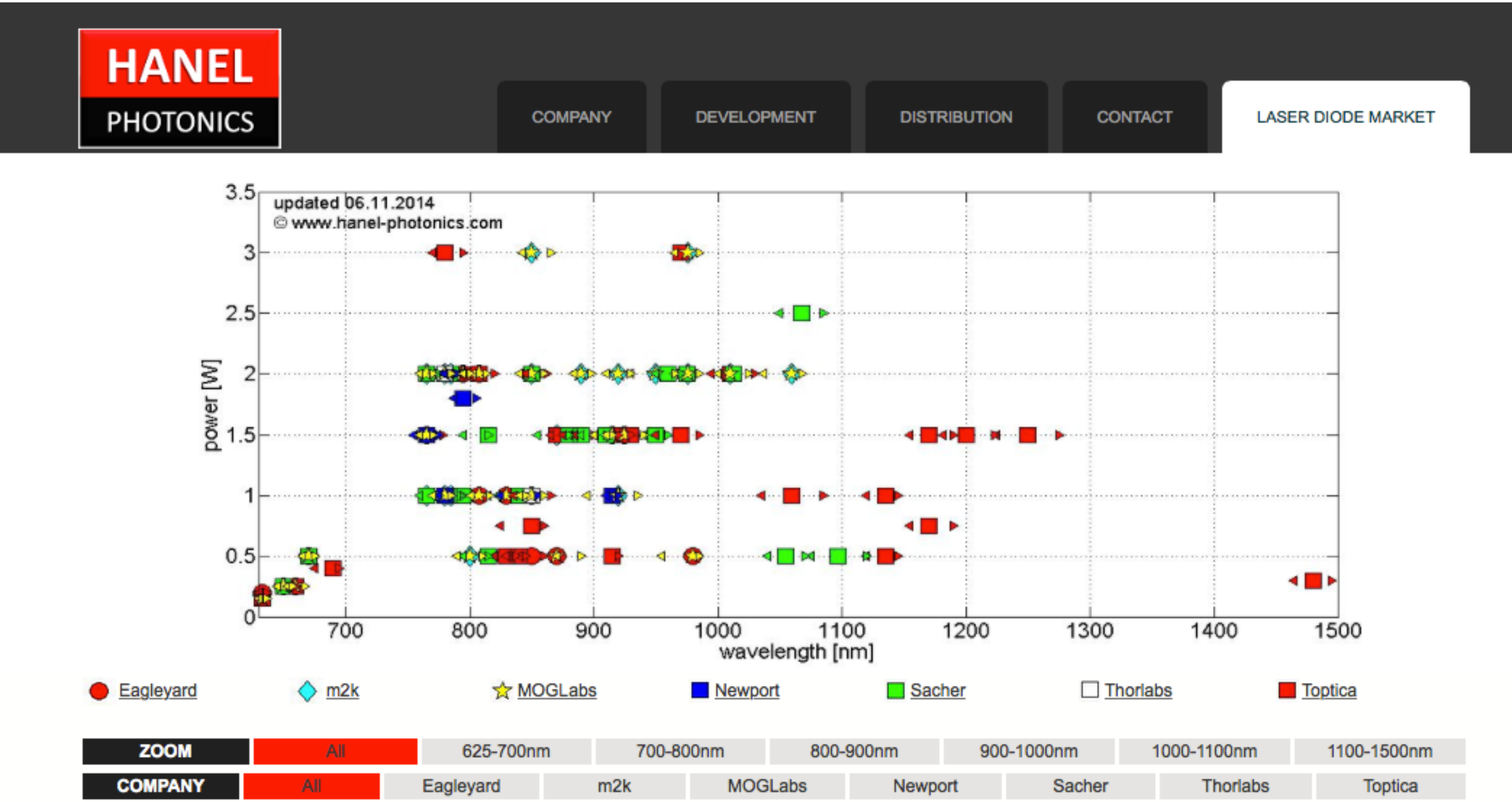
Ytterbium Doped Fiber Amplifier, Single Polarization PM OEM module

Model no.: YDFA-1064-SPM (HP)

Optical parameters (at 25°C)

Parameter	Specification	Unit
Optimized for amplifying CW signals at wavelength	1064	nm
Output power (in 5-20 mW input signal range)	> 325	mW
Output polarization extinction ratio	> 15	dB
Tap ratio for output tap coupler relative to output signal	-20	dB

Semiconductor tapered amplifiers



Semiconductor tapered amplifiers

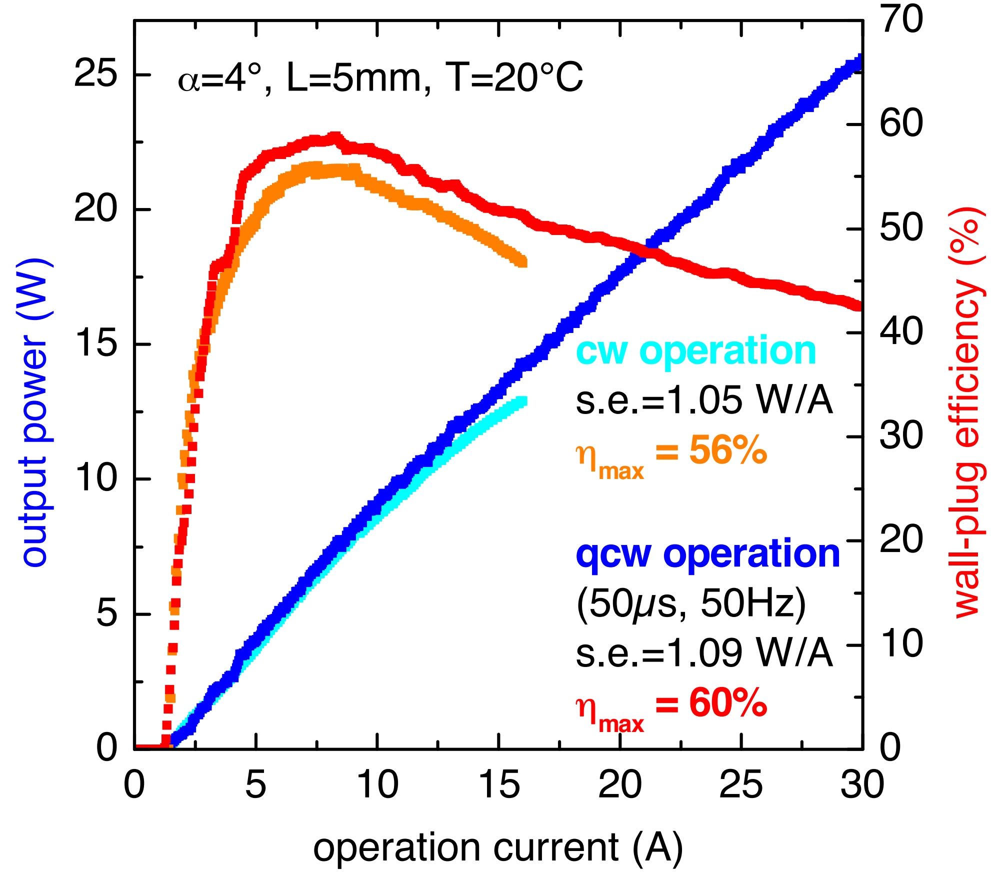
m2k Laser
High-Brightness Diode-Lasers

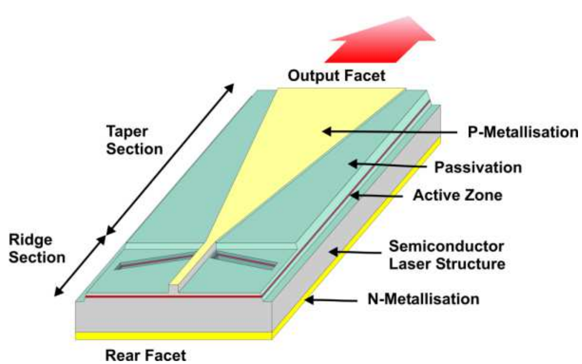
Characterisation – cw and qcw operation

Efficiency nearly comparable to broad-area lasers.

- 5mm resonator length
- coating: 1% / 95%

=> 60% wallplug efficiency

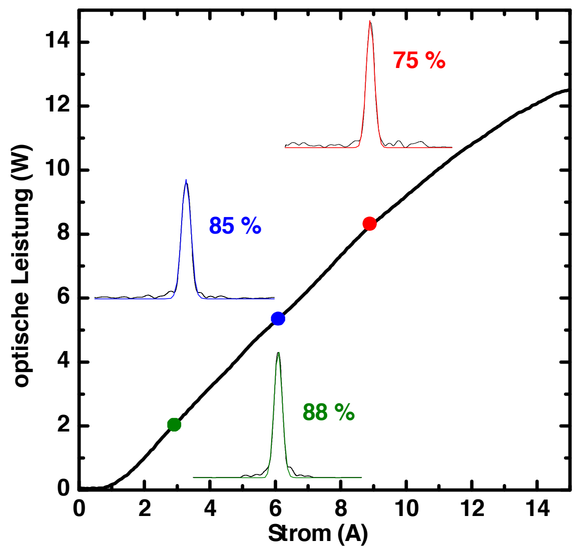




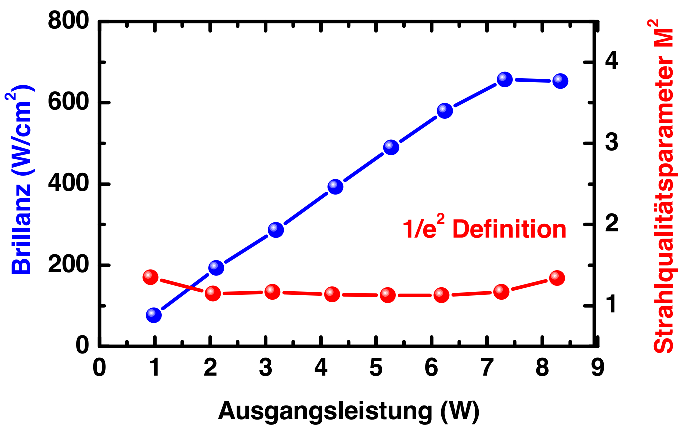
Semiconductor tapered amplifiers

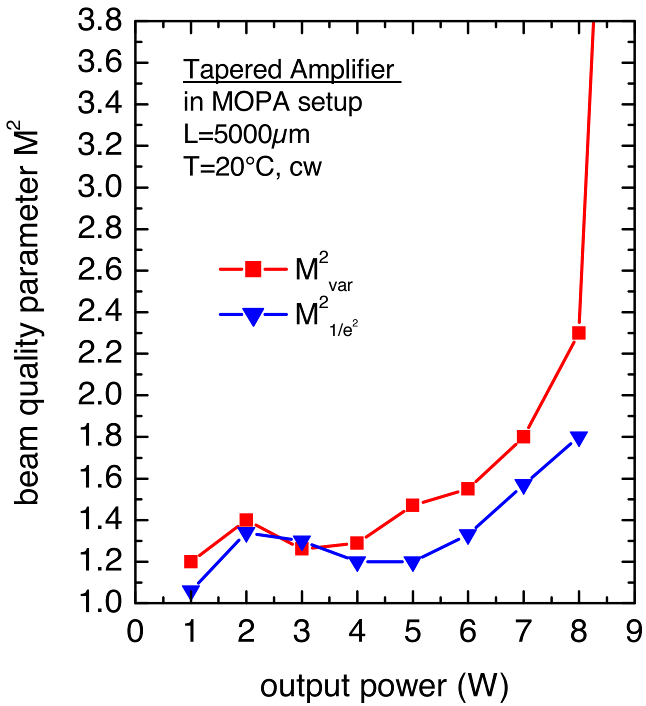
m2k Laser
High-Brightness Diode-Lasers

Characterisation – beam quality measurements



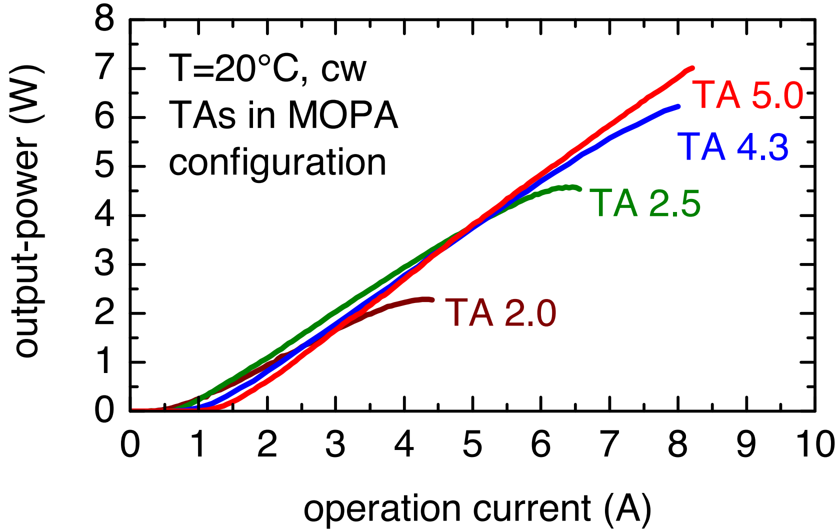
There are different kinds of measurements and definitions in the literature!

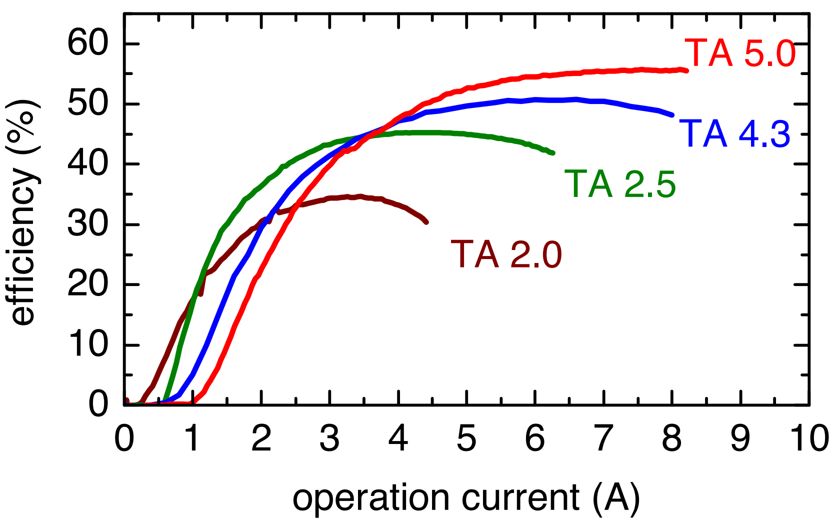




Semiconductor tapered amplifiers

MOPA – Performance





Higher power classes by longer resonators.

Design	TA 2.0	TA 2.5	TA 4.3	TA 5.0
I_{th} (mA)	0.6	0.7	1.1	1.4
s.e. (W/A)	0.70	0.91	0.98	1.06
η_{max} (%)	35	45	50.8	55.8
P_{max} (W)	2.3	4.6	>6.2	>7.0
Thermal rollover at (A)	3.5	4.6	6.6	>8

MOPA – spectral performance

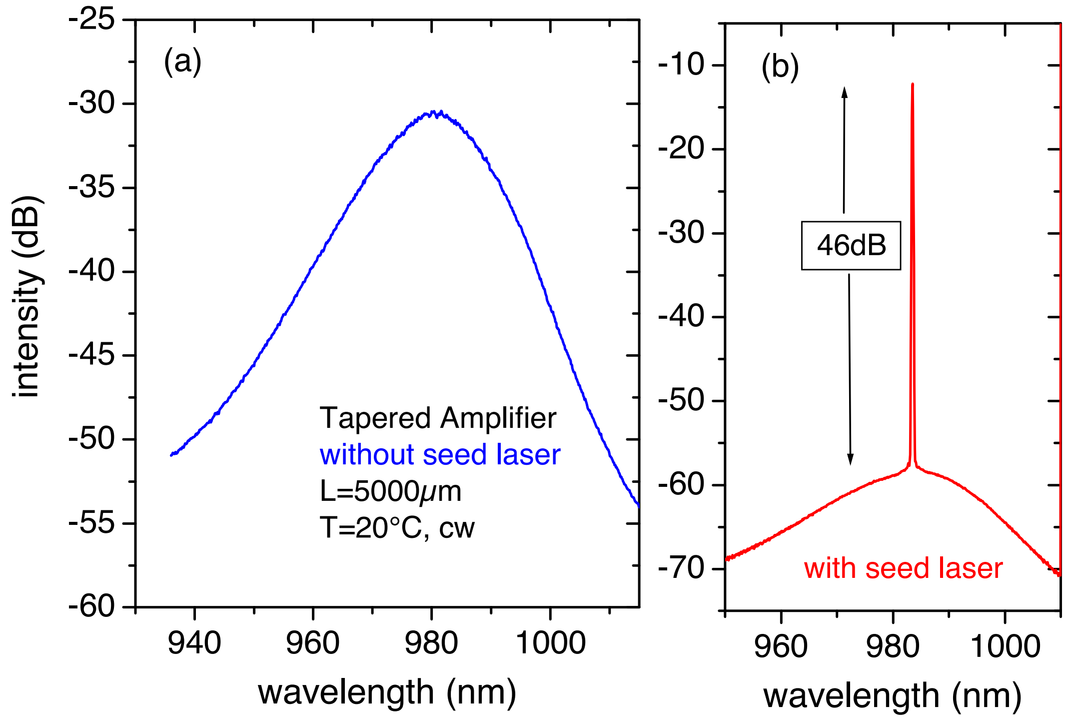
(a) Spectrum without seeder

No laser peaks visible

⇒ Really low antireflection values <0.01%

(b) TA5.0 with Seedlaser

- No additional side peaks
- Sidemode suppression of 46dB
- Spectral width <0.1nm (limited by optical spectrum analyzer)



Semiconductor tapered amplifiers -4

m2k Laser
High-Brightness Diode-Lasers

Packaging of Tapered Amplifiers

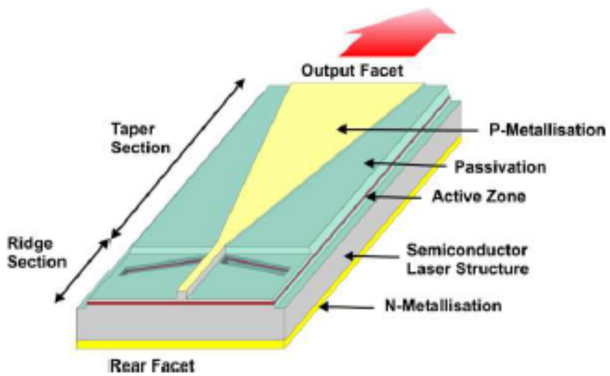
C-mount packaging with different thickness of the c-mounts is available. All diodes are soldered on submount by hard solder followed by soft soldering of submount on c-mount.

The DHP mount can be ordered in several stages:

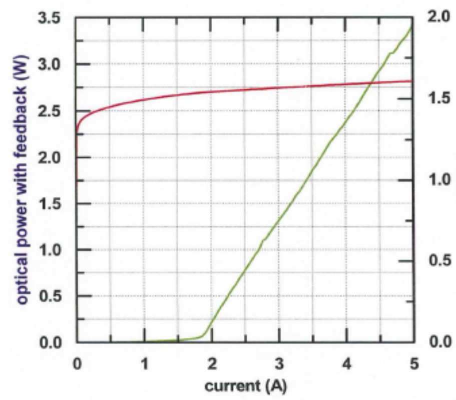
- The DHP-inset (DHP-I) offers a better heat dissipation by a bigger gold coated copper block in comparison to c-mount designs. The DHP-I mount is fixed by two screws on the left and right hand sides of the copper block whereas the c-mount design offers only a srew hole directly below the chip.
- The DHP-inset can be fixed in the DHP-frame (DHP-F-option). This package offers a good stability and protection of the chip. Also the connections of the diode are already fixed.

Resonator lengths:

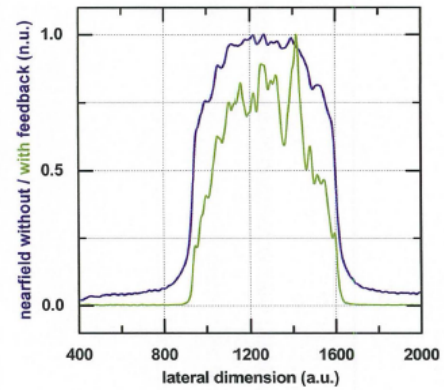
500mW	=>	2.0mm
1000mW	=>	2.5mm
2000mW	=>	4.3mm
3000mW	=>	5.0mm



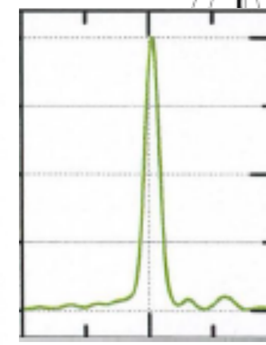
(a)



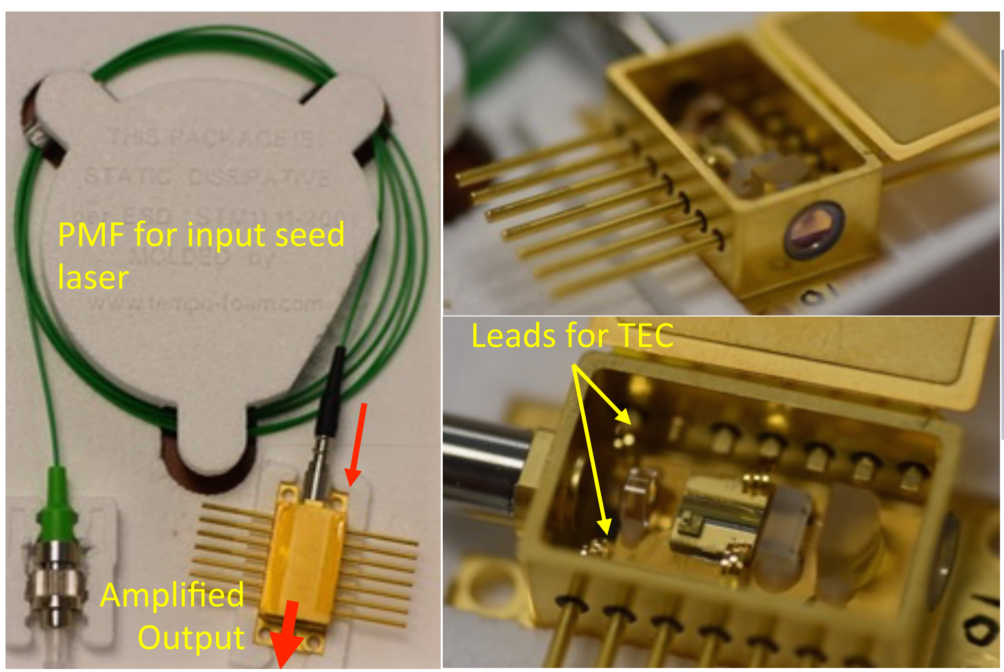
(b)

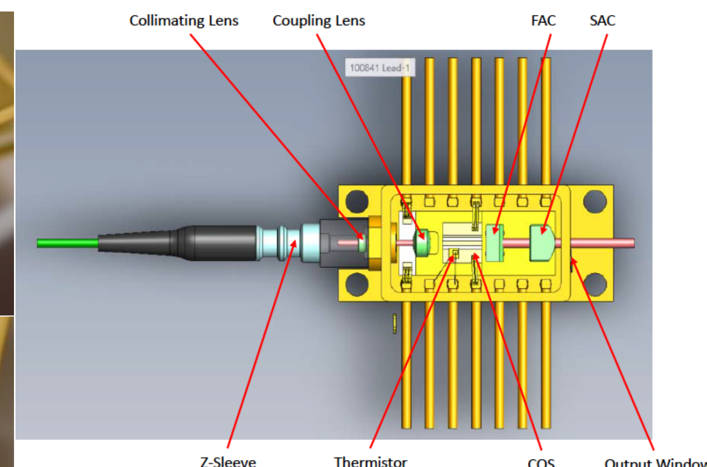


(c)



(d)





PMF – Polarization Maintaining Fiber
FAC – Fast Axis Collimator
SAC – Slow Axis Collimator
COS – Chip on Submount
TEC – Thermoelectric Cooler

Ferdinand-Braun Institute

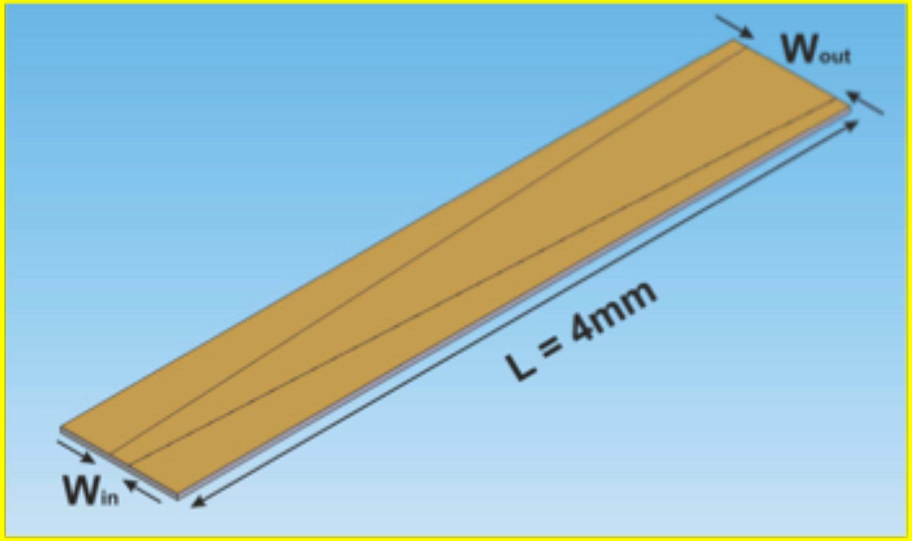


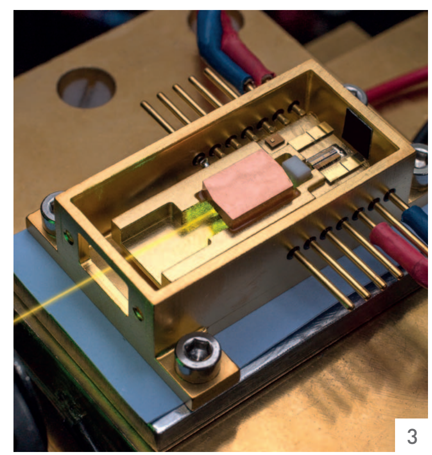
Fig. 1. Illustration of a 4-mm long truncated tapered amplifier. The current is injected only into the tapered region bounded by the straight lines.

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 25, NO. 2, JANUARY 15, 2013 115

17-W Near-Diffraction-Limited 970-nm Output From a Tapered Semiconductor Optical Amplifier

Xiaozhuo Wang, Götz Erbert, *Member, IEEE*, Hans Wenzel, Paul Crump, *Senior Member, IEEE*, Bernd Eppich, Steffen Knigge, *Member, IEEE*, Peter Ressel, Arnim Ginolas, Andre Maaßdorf, and Günther Tränkle, *Member, IEEE*

Leibniz Ferdinand Braun Institut



Laser Receivers

Direct detection system:

Detector wavelength sensitivity, area and bandwidth are key

- "Large signal" – linear-mode avalanche photodiode (APD)

  Not discussed here

- Photon counting
  - Large area photomultiplier tubes (PMT)
  - Geiger-mode APD arrays (Large area due to array)
  - Linear-mode photon-sensitive HgCdTe APDs. Need to cool to 77 K.

  . Not discussed here.
  - Superconducting nanowires: Need to cool to 1-4 K.

    Not discussed here.

Photon counting detector array
Sensl Silicon (400 – 1030 nm?) APD Array

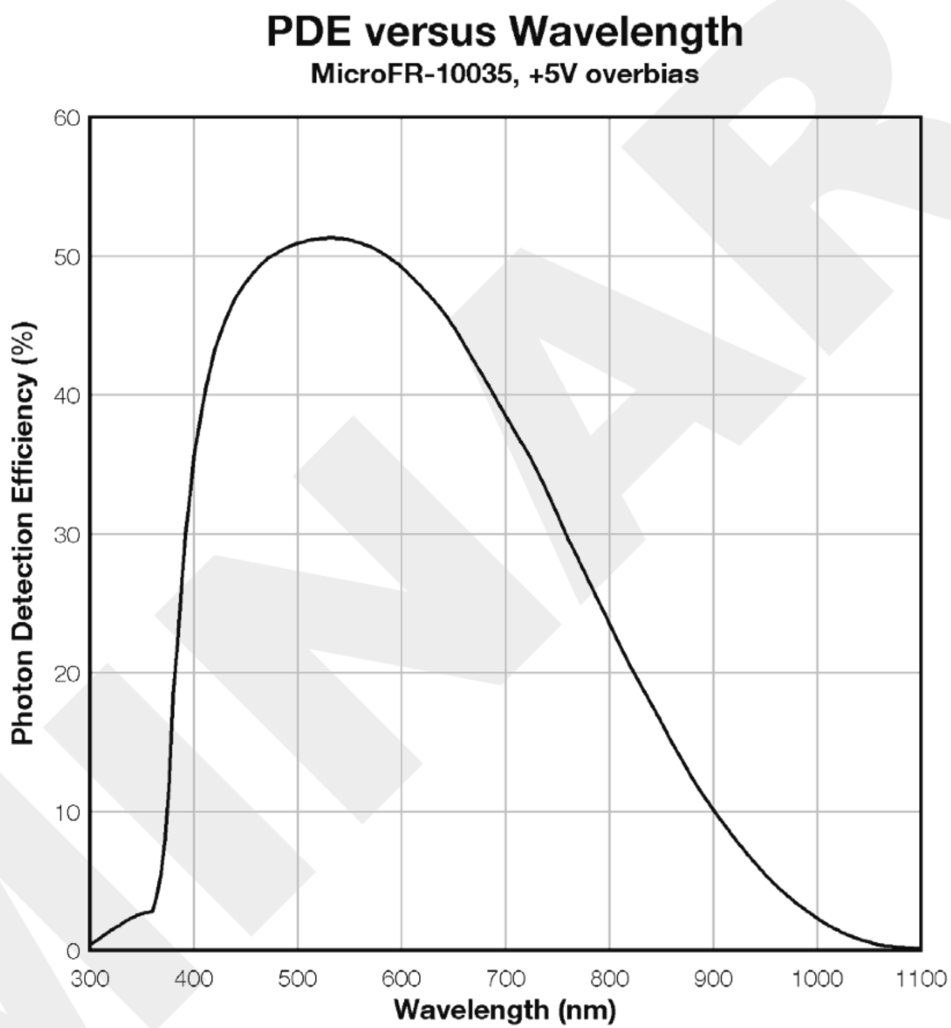
Detector: Sensl MicroFM-SMA-10020
Lot # 131218

Active Area: 1mm x 1mm
# of Cells: 1144
Fill Factor: 48%

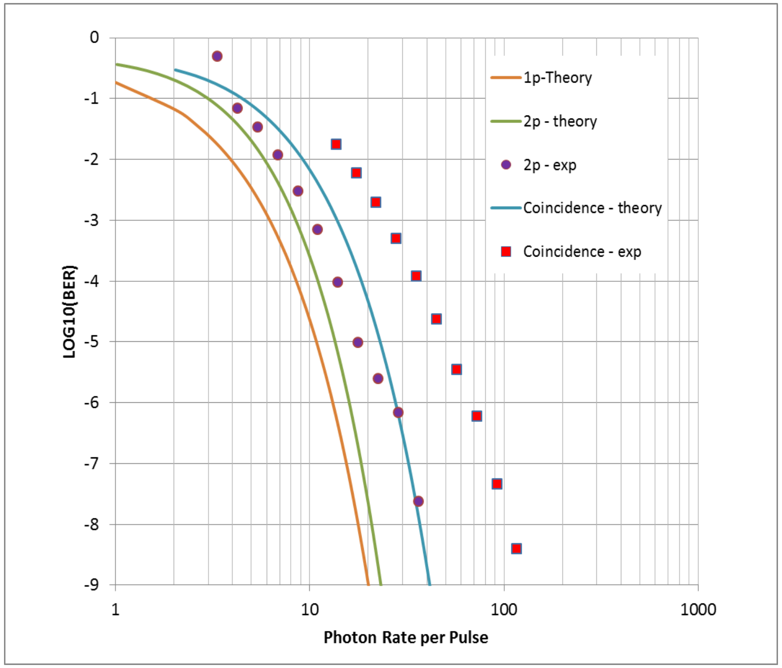
NOTE: New “Red” version available with higher near-IR QE.

Price: ~ $500.00

Sensl – photon detection efficiency (PDE) "Red sensitive" wavelength response



Sensl APD array
Communication performance (@850 nm)



RZ-OOK 100 Mbps data rate with PRBS=2^31-1
Operated with similar results to 400 Mbps

1."Novel photon-counting detectors for free-space communication" M. A. Krainak ; G. Yang ; X. Sun ; W. Lu ; S. Merritt ; J. Beck Proc. SPIE 9739, Free-Space Laser Communication and Atmospheric Propagation XXVIII, 97390T (March 15, 2016); doi: 10.1117/12.2213190

2. "Low noise, free running, high rate photon counting for space communication and ranging" Wei Lu ; Michael A. Krainak ; Guangning Yang ; Xiaoli Sun ; Scott Merritt Proc. SPIE 9858, Advanced Photon Counting Techniques X, 98580T (May 5, 2016); doi: 10.1117/12.2225925

Sensl timing jitter = 65 ps

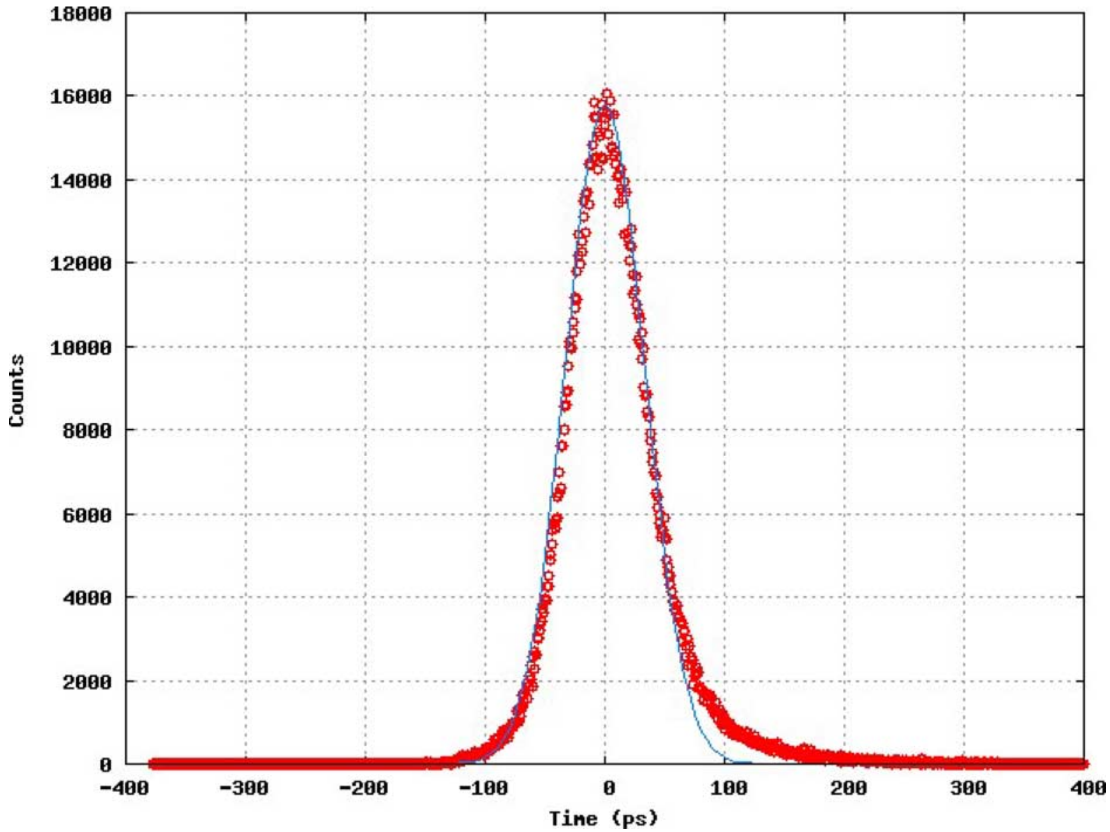


Fig. 8. Jitter histogram from SPM2 with fitted Guassian curve. The FWHM is 65 ps.

“Performance of 1-mm Silicon Photomultiplier” A. G. Stewart, V. Saveliev, S. J. Bellis, D. J. Herbert, P. J. Hughes, and J. C. Jackson
IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 44, NO. 2, FEBRUARY 2008 157

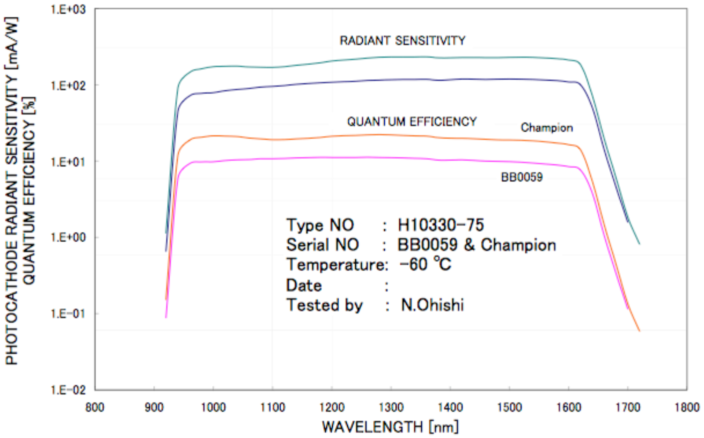
Hamamatsu InGaAs Near Infrared Photomultiplier Tubes
- Device Description

TE cooled (turn-key operation), QE~18% (custom device) at 950-1600 nm

H10330-75 TEC cooled with no vacuum pump

HV supply and PMT housing

TO-8 PMT package with transmissive photocathode



Devices on hand:
s/n BB0059 (QE=10%)
s/n BB0085 (18%)
s/n BC0018 (12%)
(currently used)
s/n BC0015 (12%)
s/n BC???? (8%)
s/n BC???? (3%)

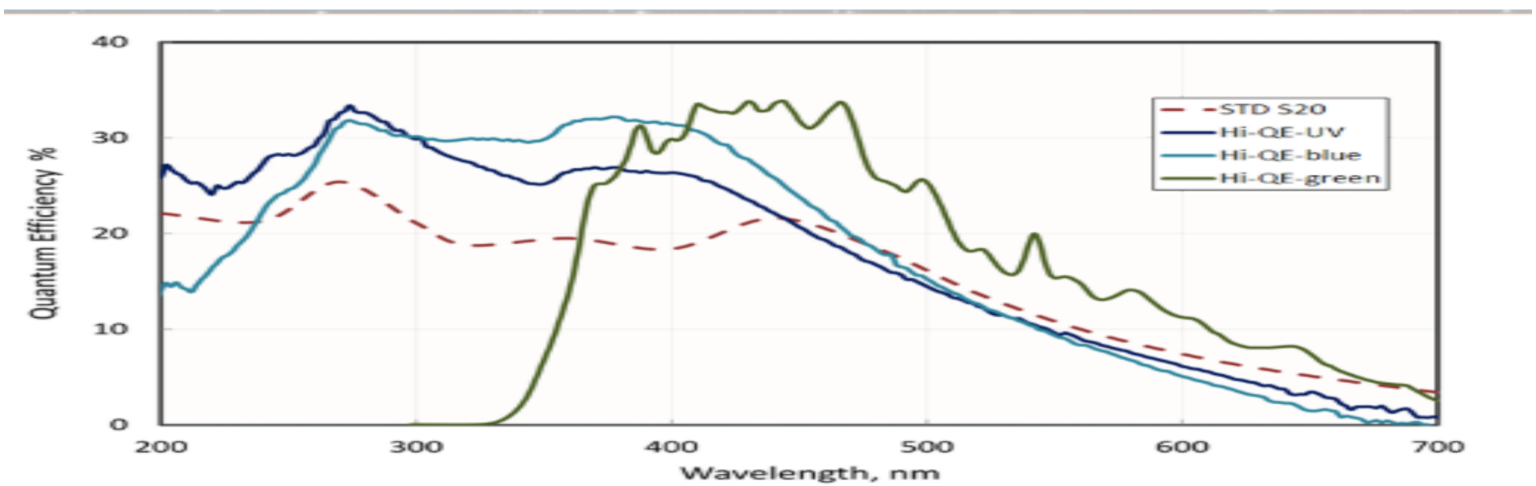
Photon Counting Performance

Spec	**InGaAs NIR-PMT**
QE	18%
Dark Cts	8e5/s
Active Area	1.6 mm
Max cts/s	30e6/s
Afterpulse	<0.1%
Bias	800 volts
Lifetime	TBD
Availability	Commercial
Price/ea	$60K
TRL	5
Status	In use, airborne experiments

Microchannel plate PMT
(350 – 700 nm)

MCP-PMT

The MCP-PMT Photon Detector brings together two fast photonic timing detection technologies into a single sensor. An 18mm MCP and a photocathode are used in combination with a single anode. The unit also offers magnetic resistance to ~3 Tesla, with jitter ~ 130pS FWHM.



Coherent receivers

Beyond the scope of “laser and detectors” talk

But “simple” idea is:

$|\text{Signal} + \text{LO}|^2$ => cross product = Signal*LO

Thus we “mix” (i.e. multiply) the signal and LO on a “square law” detector

“Square law” detector is typically a high speed PIN (positive intrinsic negative) semiconductor detector.

“Gain” comes from a “big” LO relative to a “small” signal

LO = Local Oscillator

Coherent receivers

Definitions:

Differential Phase Shift Keying (DPSK):
"Trick" is to operate at one fixed clock frequency and delay the signal one bit with a "delay line interferometer". Then => "mix" the signal with a delayed version of itself.

Heterodyne: Mix with LO to give a fixed Intermediate frequency (IF).

Homodyne: Mix with LO at the exact same frequency (i.e. IF =0 also called "baseband")

Intradyne: Mix with LO at variable frequencies. I call this – "use a digital signal processor (DSP) to figure it out".

I and Q: In-phase and Quadrature (i.e. 90 degree phase shifted)

Constellation diagram: NOT a set of CUBESats in space. Rather a plot of the possible symbols that may be selected by a given modulation scheme as points in the complex (real and imaginary) plane.

Coherent receivers

- Because we are "mixing" signals to recover the temporal phase, we need "single spatial mode" => in short => we typically need single-mode fiber. At 1550 nm wavelength "single (spatial) mode" fiber is typically 9 microns in diameter (standard is SMF-28 fiber).
- Due to atmospheric turbulence, we need "adaptive optics" to efficiently focus the light into a single-mode fiber

Wrapping up:

There are plenty of commercial, high speed (multi Gigabit), erbium fiber preamplifiers and PIN diode detectors

Example: Coherent receiver detector

Optical Components

100 GHz Single High-speed Photodetector

XPDV412xR

High-Speed Detectors and Receivers

The XPDV412xR family contains two photodetector devices, with optimized ultrafast photodiodes with up to 100 GHz bandwidth. Both photodetectors, the XPDV4120 (f3dB > 90 GHz) and XPDV4121R (f3dB >100 GHz), are designed with waveguide-integrated photodiodes and show an extremely flat frequency response in power and in phase. The on-chip integrated bias network with optimized RF design in particular, ensures undisturbed frequency response from DC to the 3 dB cut-off frequency and saves costs for internal bias-tees. The devices are especially developed for optimal RF performance revealing virtually no pulse response ringing.

Both photodetectors are characterized in the frequency domain by using a heterodyne technique. In the time domain, a femtosecond pulse source and a 65 GHz sampling oscilloscope are used to measure the pulse response.