NORLASE
Compact Diode Systems

NEXT-GENERATION VISIBLE LASERS FOR HOLOGRAPHY

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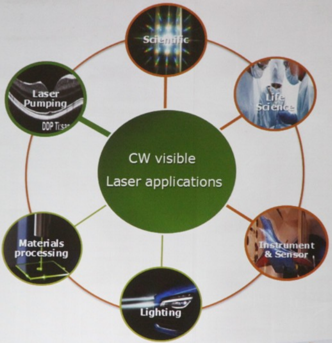
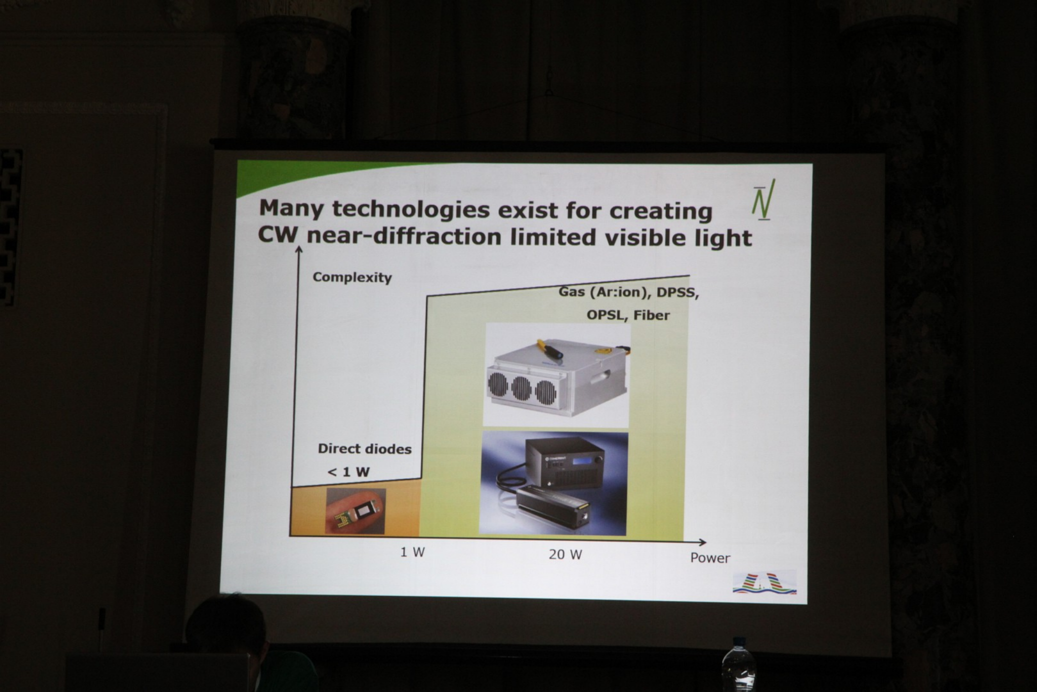
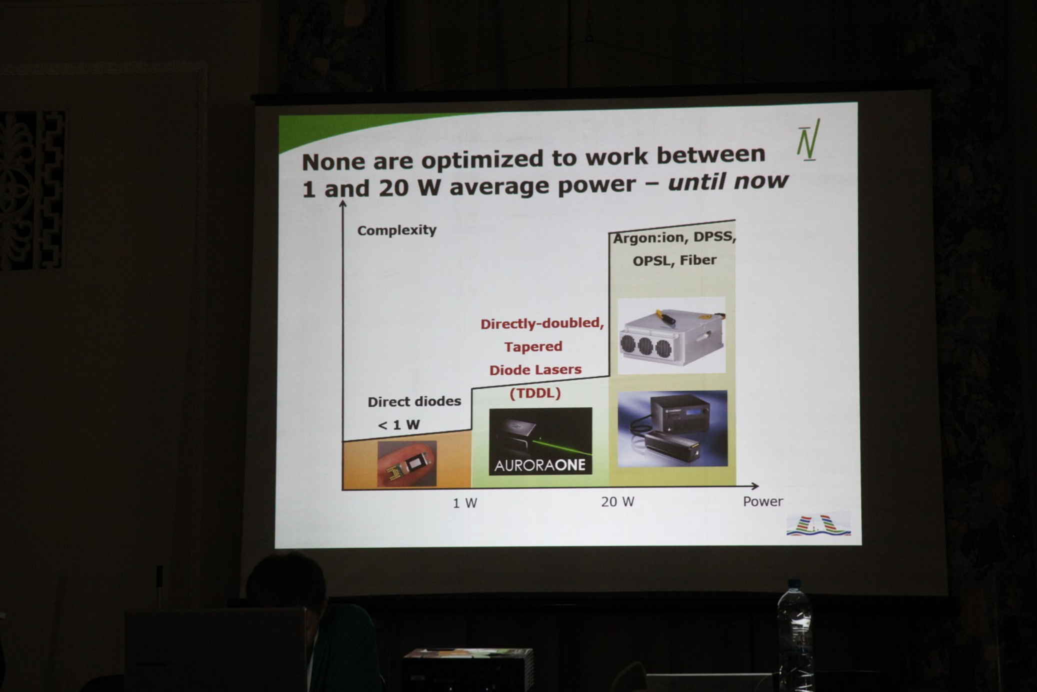
Motivation

Simplest laser architecture to reach applications for **CW, visible lasers with high beam quality** <u>**and**</u> ***> 1W of average power***




Many technologies exist for creating
CW near-diffraction limited visible light
Complexity
Gas (Ar:ion), DPSS,
OPSL, Fiber
Direct diodes
< 1 W
1 W
20 W
Power


None are optimized to work between
1 and 20 W average power – *until now*
Complexity
Argon:ion, DPSS, OPSL, Fiber
Directly-doubled, Tapered Diode Lasers (TDDL)
Direct diodes < 1 W
AURORAONE
1 W
20 W
Power

Overview

Part I: Technology

- Why diode lasers?
- How to break the ~ 1W (CW) barrier for high-brightness, visible direct-diode based lasers – Tapered Direct-Doubled Lasers (TDDLs)

Part II: Application Example

- First hologram made with TDDL

Key advantages of diode lasers

- **Output power and efficiency**
  - mW to kW depending on laser type & wavelength
  - ***CW operation or pulsed mode***
  - direct electrical pumping with high wall-plug efficiencies

A. Müller, S. Marschall, O. B. Jensen, J. Fricke, H. Wenzel, B. Sumpf, and P. E. Andersen,
"Diode laser based light sources for biomedical applications", Laser Photonics Rev. (2012) DOI:10.1002/lpor.201200051

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  - 360 nm - 2 µm with III-V compound semiconductors
  - ***selectable wavelength within the gain spectrum***
  - ***narrow emission bandwidths by intrinsic or external feedback***
  - diffraction-limited output at the expense of output power

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  - dimensions of only a few mm^3
  - chip technology enables affordable mass-production and wide-spread applications

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➢ ***Simplest architecture to go from electrons to photons***

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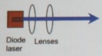
How have diode lasers been used to generate near-diffraction-limited visible CW light?

Y. Kaneda *et al.*, Opt. Lett. **33**, 1705-1707 (2008)

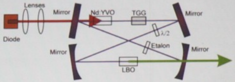
How have diode lasers been used to generate near-diffraction-limited visible CW light?

- Direct-diode

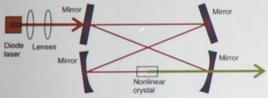


Limited power when high beam quality is required (< 1 W)

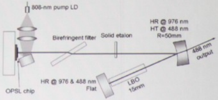
- As pumps for diode-pumped solid state lasers (DPSSL)



- As pumps for external cavity frequency conversion



- As pumps and gain material for optically-pumped semiconductor lasers (OPSL)



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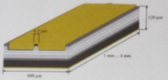
Semiconductor laser diodes: Edge-emitting types and their pros and cons

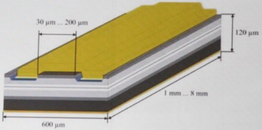
The dilemma:

SM Ridge waveguide laser diodes:



- great beam quality, near single-mode emission √
- inexpensive √
- optical output power of only 1-2 W (Near-IR) and < 1 W in the visible (-)

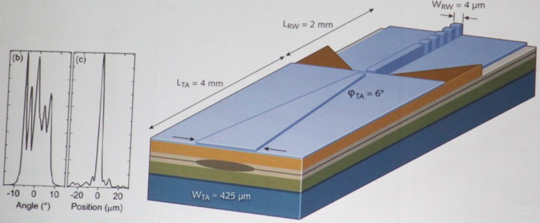
Broad area laser diodes:

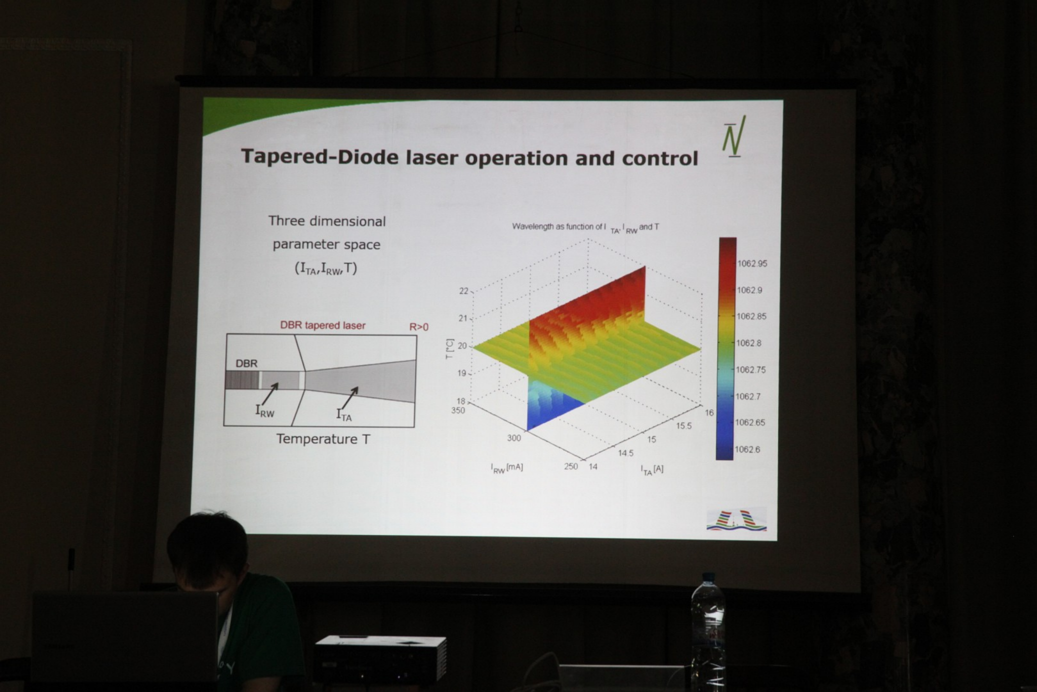


- great efficiency and power, > 20W (Near-IR) √
- compact and robust √
- inexpensive √
- poor spatial quality (-)

Solution: Tapered Semiconductor Laser

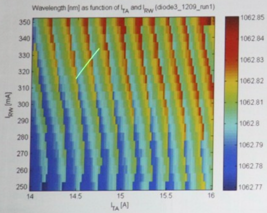
- spatial single-mode emission (~ 70% in diffraction-limited beam) √
- frequency selective component at rear facet (< 5 pm) => single-frequency √
- output power > 10 W √

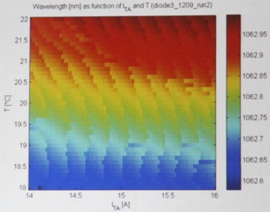


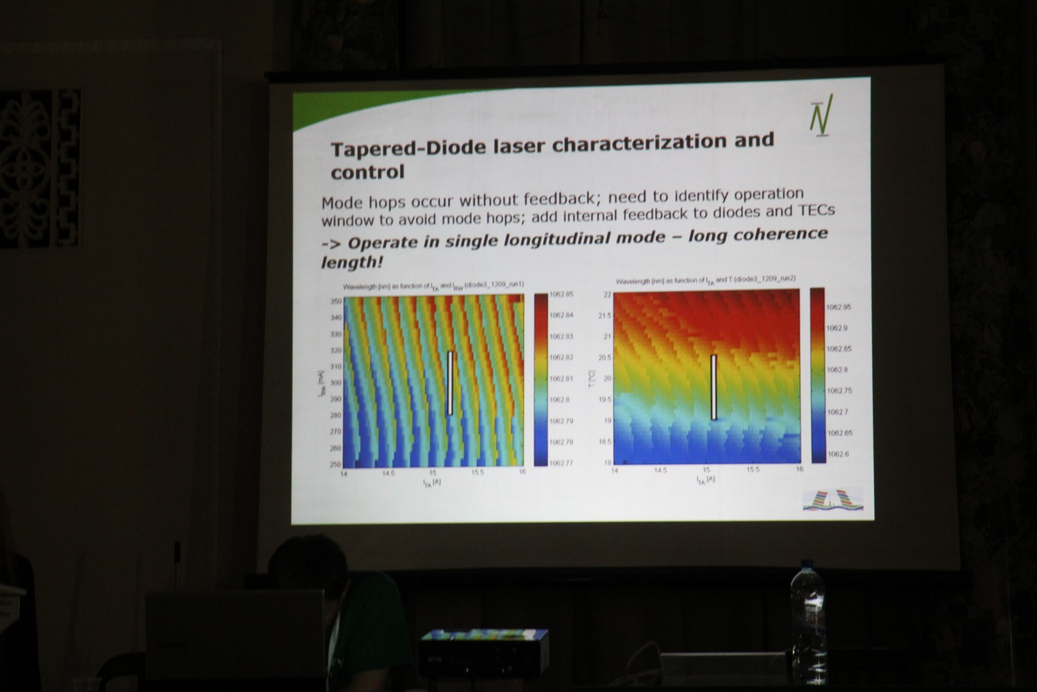

Tapered-Diode laser operation and control
Three dimensional
parameter space
(I_TA, I_RW, T)
DBR tapered laser
R>0
DBR
I_RW
I_TA
Temperature T
Wavelength as function of I_TA, I_RW and T
T [°C]
22
21
20
19
18
350
300
250
I_RW [mA]
14
14.5
15
15.5
16
I_TA [A]
1062.95
1062.9
1062.85
1062.8
1062.75
1062.7
1062.65
1062.6

Tapered-Diode laser characterization and control

Mode hops occur without feedback; need to identify operation window to avoid mode hops; add internal feedback to diodes and TECs

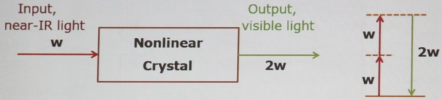





Tapered-Diode laser characterization and control
Mode hops occur without feedback; need to identify operation window to avoid mode hops; add internal feedback to diodes and TECs
-> Operate in single longitudinal mode – long coherence length!
Wavelength [nm] as function of I_TA and I_RW (diode3_1209_run1)
I_TA [A]
Wavelength [nm] as function of I_TA and T (diode3_1209_run2)
T [°C]
I_TA [A]

How to get visible light: Frequency conversion

- Frequency doubling



- Power of generated waves depends on
  - fundamental power P_ω
  - crystal length L
  - nonlinear coefficient d_{eff}
  - focusing condition ($h_{max} = 1.07$ @ $z_{Rayleigh} = L/5.68$)
  - phase-matching condition ($\Delta k = 0$)

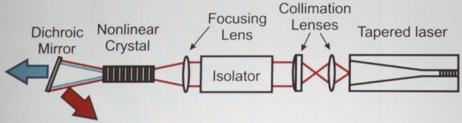
$$I_{2\omega} = \frac{2\pi^2 d_{eff}^2}{n_{2\omega} n_\omega^2 \lambda_{2\omega}^2 \varepsilon_0 c} I_\omega^2 L^2 \operatorname{sinc}^2\left(\frac{\Delta k L}{2}\right)$$

$$P_{2\omega} = \frac{16\pi^2 d_{eff}^2}{n_{2\omega} n_\omega \lambda_\omega^3 \varepsilon_0 c} P_\omega^2 L h(\sigma, \beta, \kappa, \xi, \mu)$$

- Quasi-phase-matching tolerances ~ $1/L$
  => high-power diode lasers with narrow emission bandwidth

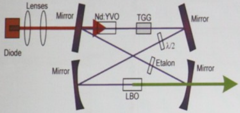
Putting it together -
Tapered direct-doubled diodes: A new class of lasers 'TDDL'

- No free space cavity -> stable operation
- Tapered diode with high beam quality
- Single-pass frequency doubling, feedback loop for stabilization
- Blue (465 & 488 nm), Green (532 nm), Yellow (560 nm)
- Long coherence length – measured to 1.5 m (measurement-limited)



Technology comparison

DPSS: Diode Pumped Solid State Laser



- ✘ Limited wavelengths
- ✘ Low efficiency
- ✘ Complex => High Cost
- ✘ Cavity-based => Instability

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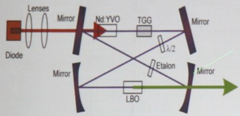

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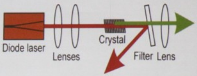
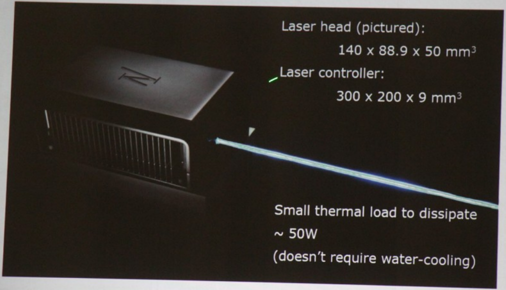
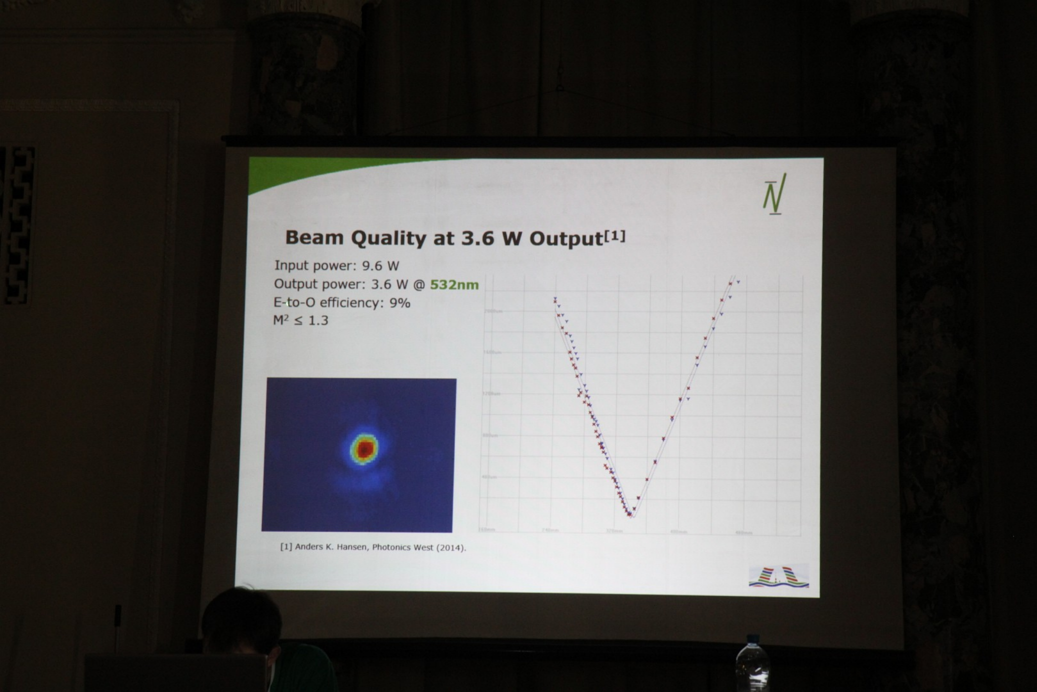
TDDL: Tapered Diode Doubled Laser



- ✓ Wavelengths between ~ 460 and 570 nm
- ✓ High efficiency
- ✓ Simple => Low(er) Cost
- ✓ No free space cavity => Stable

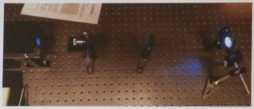
TDDL Product – Norlase AuroraOne




Beam Quality at 3.6 W Output[1]
Input power: 9.6 W
Output power: 3.6 W @ 532nm
E-to-O efficiency: 9%
M² ≤ 1.3
[1] Anders K. Hansen, Photonics West (2014).


Product roadmap:
Prototype, 2013
1 W
Market entry, 2014
0.7 W
1.5 W
3 W
Production build-up, new laser products, 2015 -16
2 W
2 W
1.0 W
4 W
Power scaling 2017
3 W
5 W
3 W
2 W
8W

First TDDL used for making a reflection hologram



Conditions:

- Set-up: Denisyuk
- Material: LitiHolo R-RT20
- Lens: 350 mm
- Laser: Norlase AuroraOne **488 nm** laser
  Power: 250 mW (~ 20 mW at plate)
  Coherence length > 1.5 m
- Exposure time: ~ 100 s
- Object: Olympic coin

Hologram

Hologram is with me – ask me if you would like to see it (but remember that this was made by a laser specialist!)

Next-generation visible lasers:

- ✓ Semiconductor based, cavity-free, single-pass
- ✓ Simple and compact
- ✓ Wide range of center wavelengths: ~ 460 – 570 nm
- ✓ Coherence length > 1.5 m
- ✓ High beam quality and stability at watt-level power

Norlase is a laser company – we are not holography experts;
let us know how we can help you

Thanks for your attention!

Michelle L. Stock, mls@norlase.com