Grating-waveguide structures and their applications in high-power laser systems

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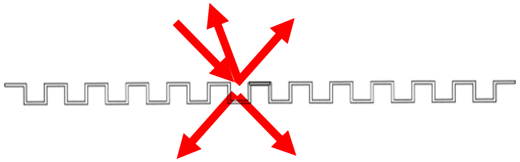
What is a Grating Waveguide Structure?

- **Answer:** Combination of a **sub-wavelength grating** and **planar waveguide**

diffraction grating (<λ)



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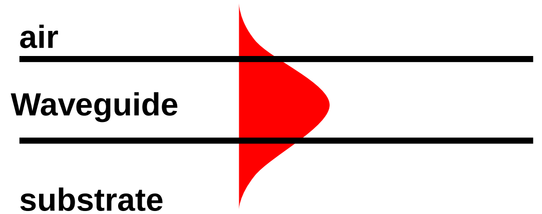
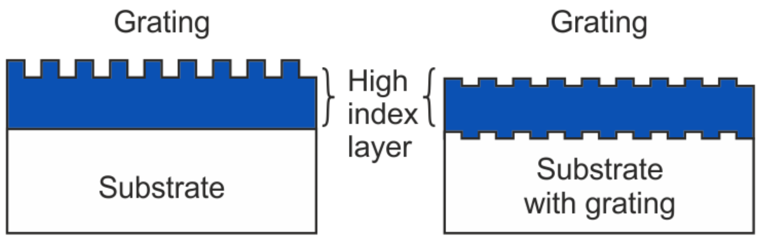
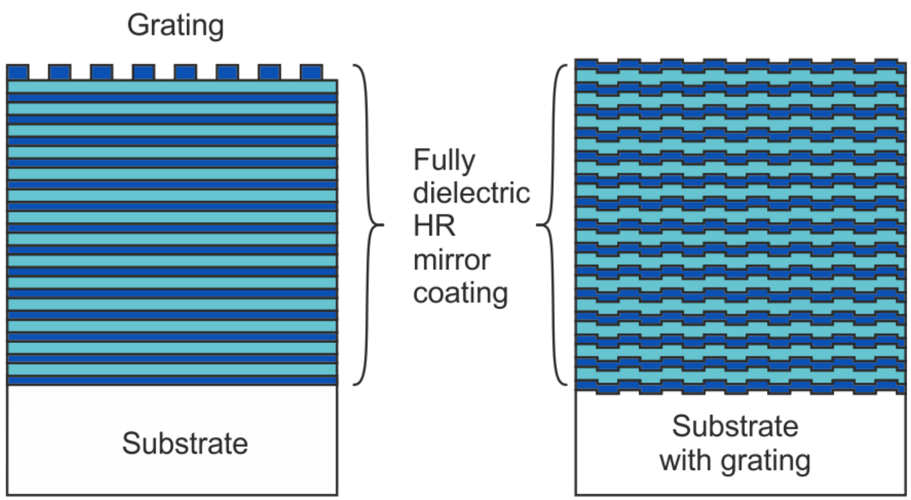
field accumulation i.e waveguide



- Single layer GWS



- Multilayer GWS



Outline

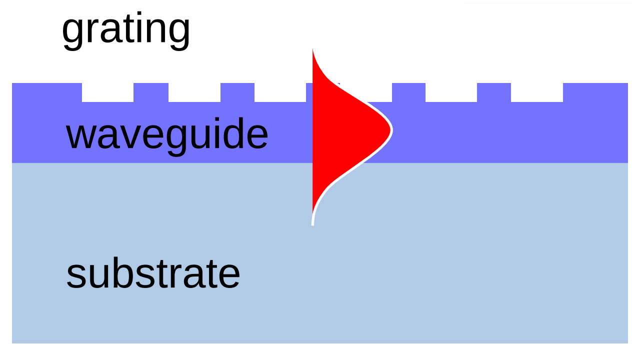
- Grating Waveguide Structure (GWS): Introduction
- Applications in high-power lasers
  - Polarization selective GWS
  - Polarization and wavelength selective GWS
- Summary

Grating Waveguide Structure: Introduction

diffraction grating (<λ)

+

field accumulation i.e waveguide



- A **GWS** is characterized by unique **<u>resonances</u>** thanks to the excitation of „true“ guided modes or leaky modes

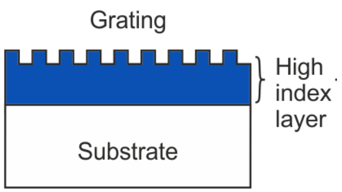
- Resonances can be in
  - **reflection**,
  - **transmission** or
  - **diffraction**

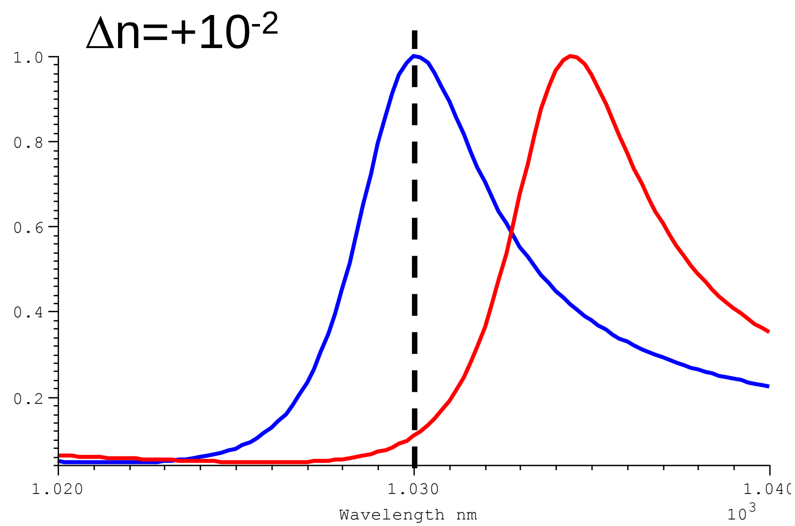
By a proper design of the GWS parameters it is possible to modulate the **reflected**, **transmistted**, or **diffracted** beam from 0 to 100% for a given <u>polarization</u>, <u>wavelength</u> and <u>angle of incidence (AOI)</u> due to ***interferences*** or ***coupling phenomena***

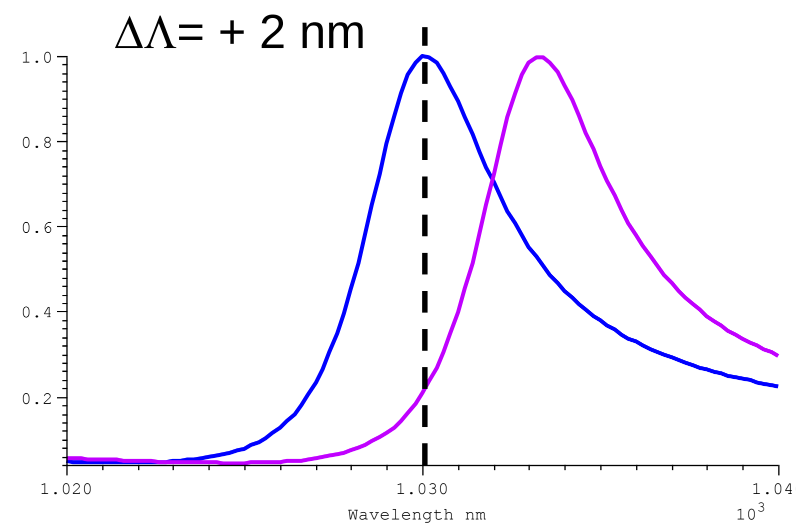
These phenomena *are very sensitive to GWS opto-geometrical parameters.* ***<u>A precise control of the manufacturing is required</u>*** to successfully transform a design to the actual GWS

Grating Waveguide Structure: Introduction

- **Opto-geometrical** parameters of a GWS are:
  - Refractive indices (cover medium, substrate and coated layers)
  - Thicknesses of coated layers
  - Grating parameters (period, duty-cycle, groove depth, shape)
- Deviation of these parameters will lead to **detrimental deviation of the function of the GWS** (e.g. spectral shift, reduced polarization selectivity, reduced diffraction efficiency, etc…)
- Examples:



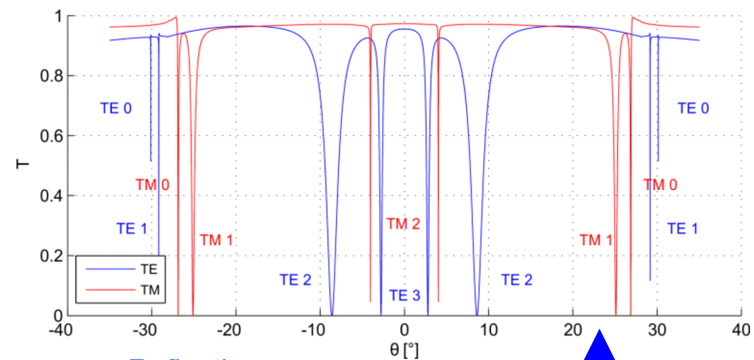


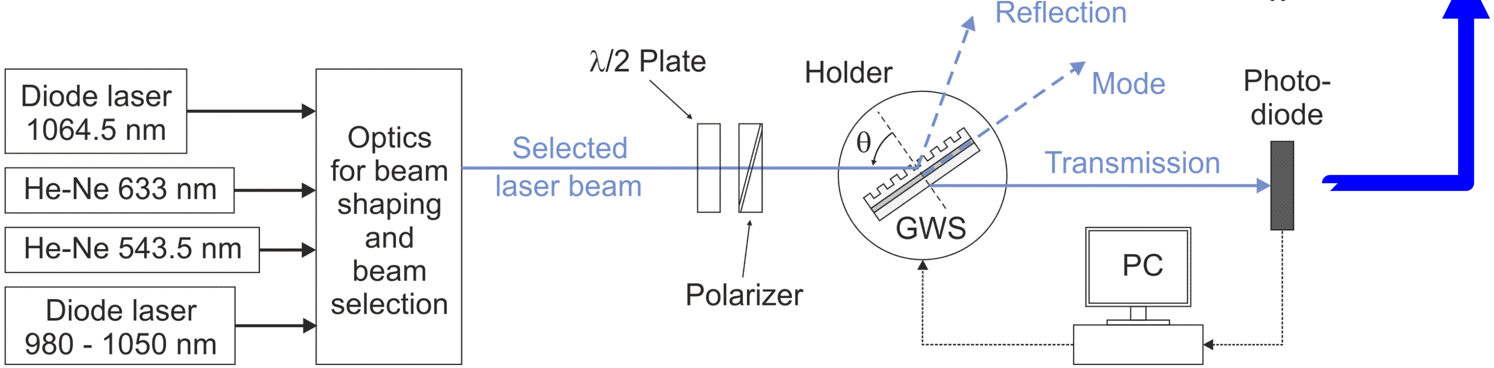


Grating Waveguide Structure: Introduction

- **Refractive indices and thicknesses** of waveguide (**coated layers**)
  - Usually specified by suppliers but not always precisely enough known for requirements in GWS design ☹
  - Better to measure them ☺

    e.g. by **“M-lines spectroscopy”**
    - Accuracy refractive index <10^{-3}
    - Accuracy layer thickness <5 nm

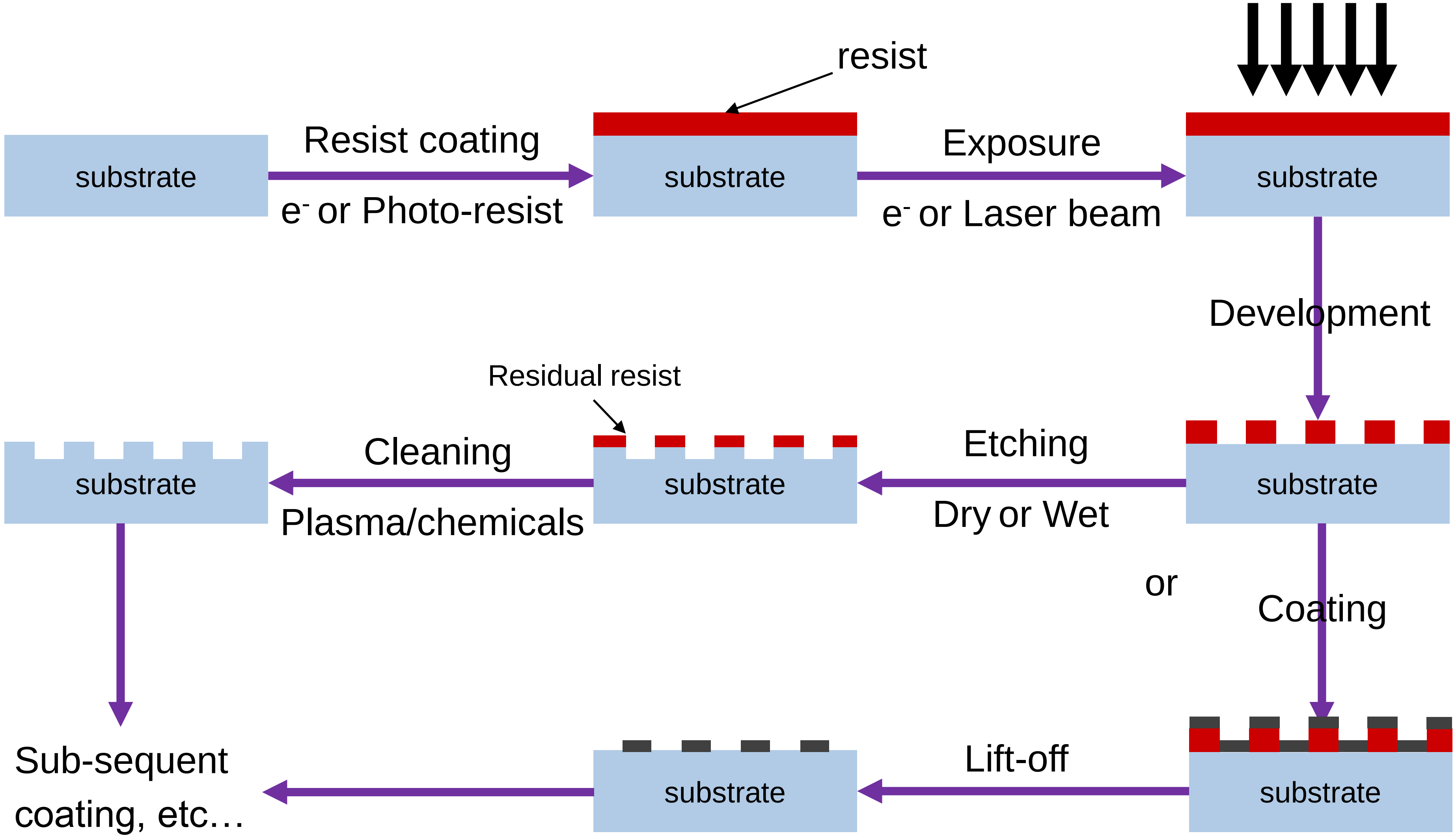




- **Grating parameters** (period, duty-cycle, groove depth, shape)
  - Depend on choice of production technique (lithography + etching) and its precision
  - Often costly process calibration required for each new fabrication run

Grating Waveguide Structure: Introduction

- **Fabrication**



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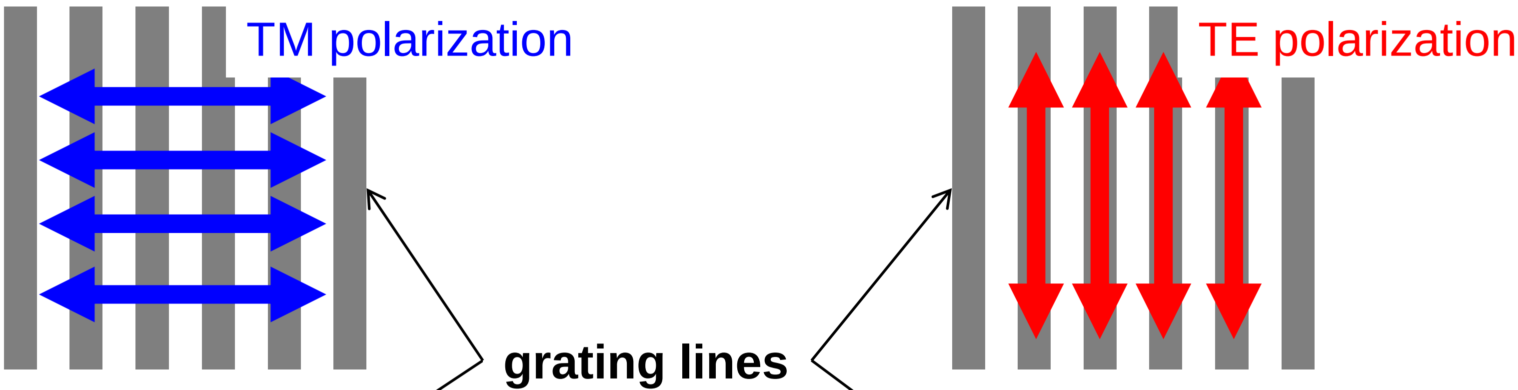
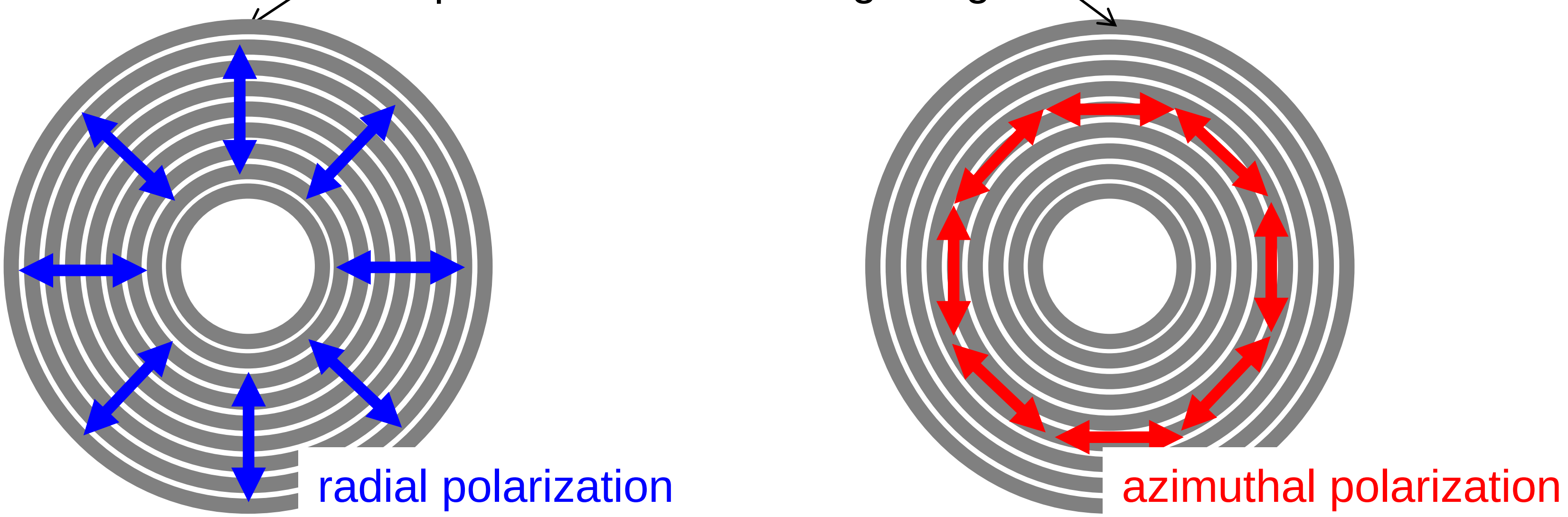
Applications in high-power lasers

- **Polarization state and gratings**
  - Linear polarization: linear gratings

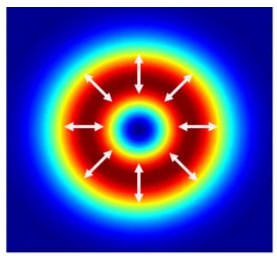


  - Radial and azimuthal polarization: circular gratings

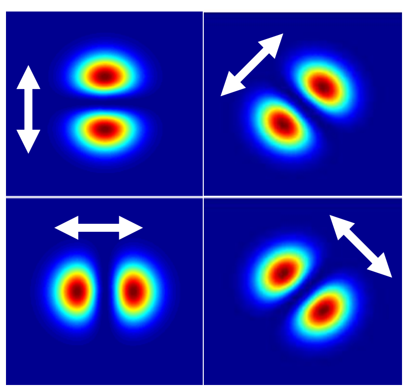


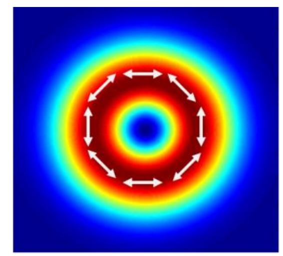
Applications in high-power lasers

- Polarization selective GWS: Generation of beams with **radial/azimuthal polarization** **(beneficial for material processing*: cutting, welding, drilling)**
    - Common state of the art polarizations are linear or circular (elliptical): homogeneous polarization state over the beam cross-section
    - Radial or azimuthal polarization = inhomogeneous polarization state over the beam cross-section

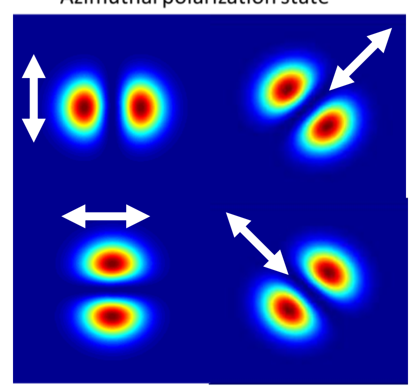


Radial polarization state





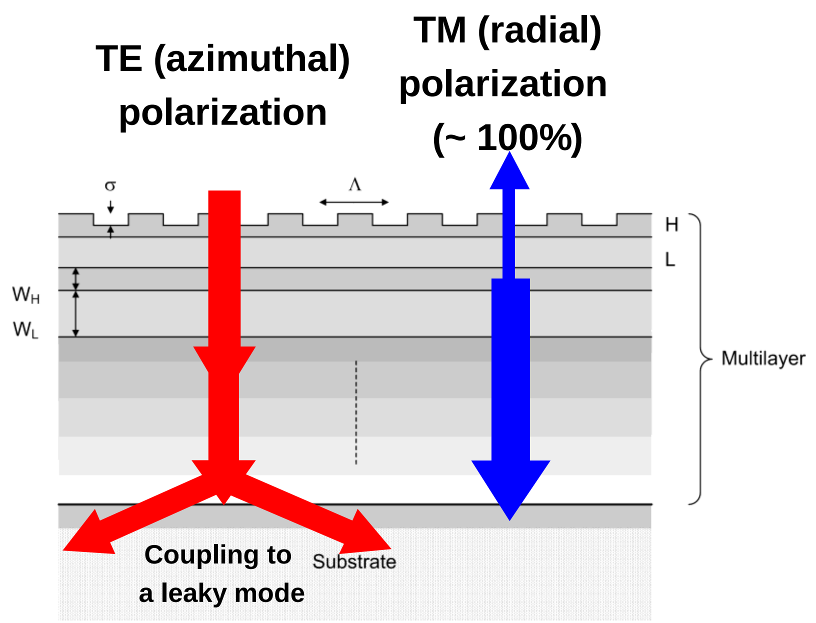
Azimuthal polarization state



* Weber et al., Phys. Procedia 12, 21 (2011)

Applications in high-power lasers

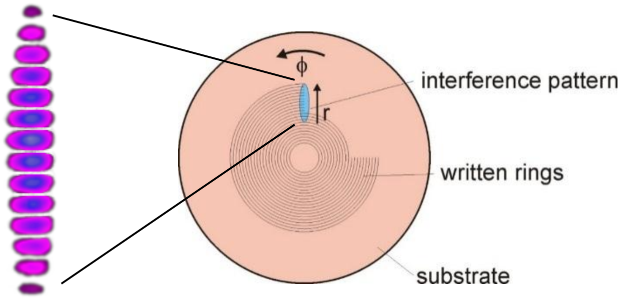
- Polarization selective GWS: generation of beams with **radial/azimuthal polarization**
  - Structure: **circular** sub-wavelength grating + fully dielectric multilayer mirror
  - Principle of leaky-mode grating mirror

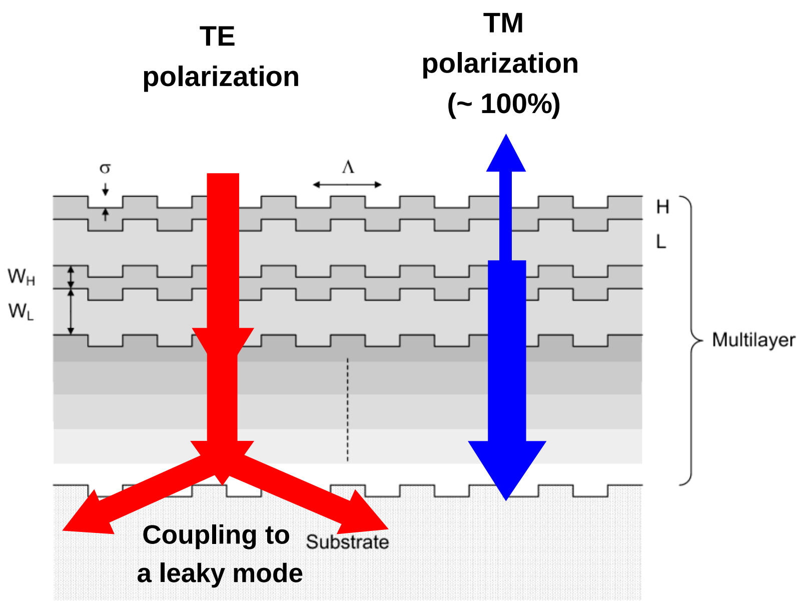


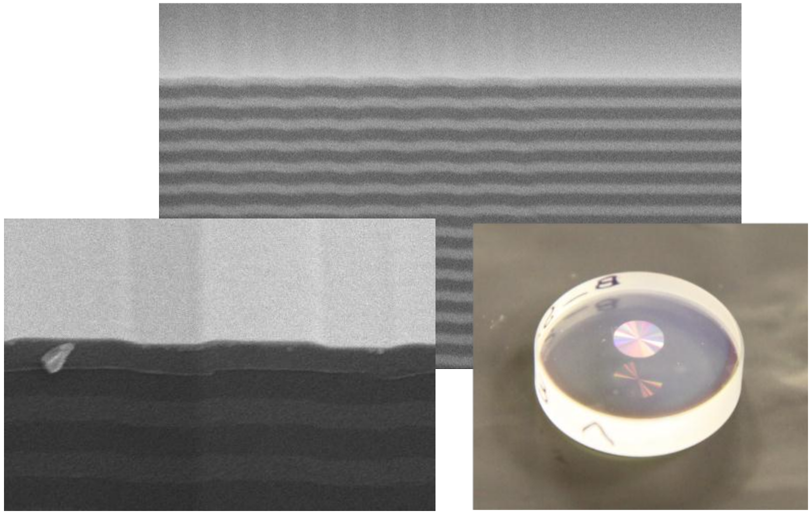
  - Reduction of the reflectivity of the undesired polarization
  - The orthogonal polarization does not „see" the grating and exhibits a reflectivity close to that of the HR mirror without grating
    - Only the polarization with the lowest losses (highest Reflectivity) will oscillate in the laser

Applications in high-power lasers

- Polarization selective GWS: generation of beams with **radial/azimuthal polarization**
  - Design & Fabrication method: **SBIL** (Scanning beam Interference Lithography) + **RIE**
    - Grating: Period=930 nm, Depth=20-25 nm
    - Multilayer: 29 (λ/4) alternating Ta_2O_5/SiO_2





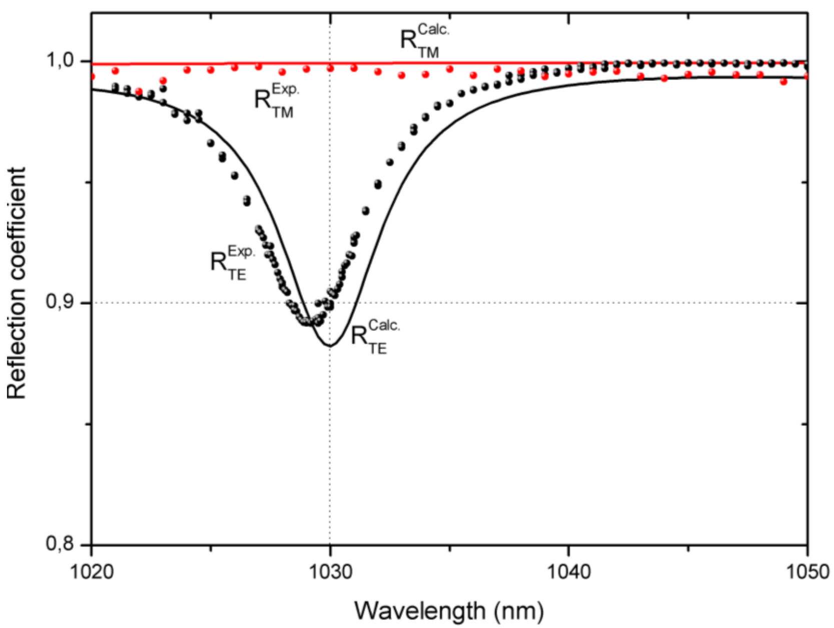


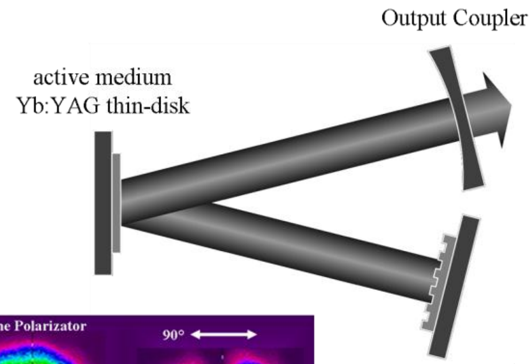
- R_{radial} = 99.92% (design)
- $R_{azimuthal}$ =88.2% (design)

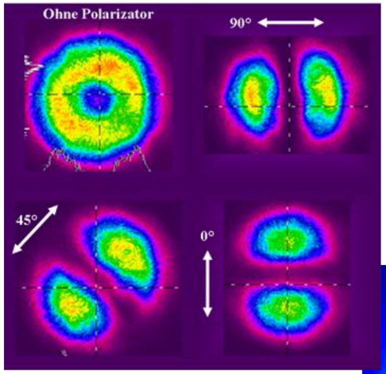
→ Generation of beams with radial polarization

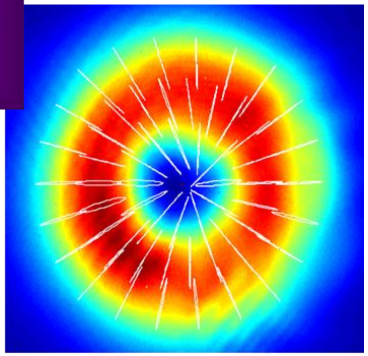
Applications in high-power lasers

- Polarization selective GWS: generation of beams with **radial/azimuthal polarization**
  - Reflectivity measurement & laser test









- R_{azim} = 99.8%+/- 0.2% (measured)
- R_{radial} = 90% +/- 0.2% (measured)
- Demonstration of up to **660 W** output power (Opt. Eff. ~ 45-50%), M^2<2.3
- DORP (degree of radial polarization): 98.5% +/-0.5%

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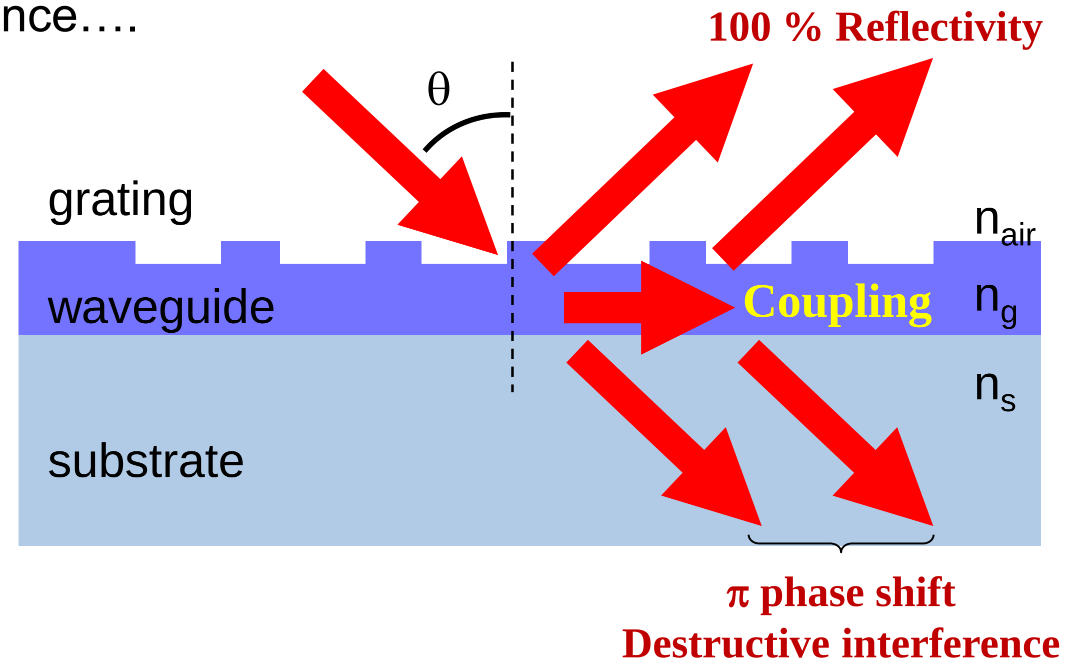
Applications in high-power lasers

- Polarization and wavelength selective GWS: narrow bandwidth and linearly polarized thin-disk laser (**beneficial for SHG**)
- The resonant reflection effect*
  - At resonance….

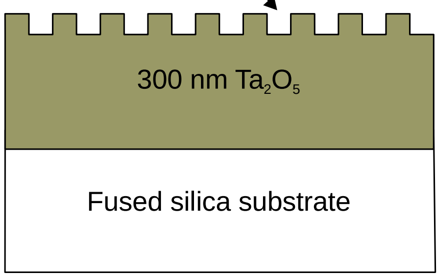


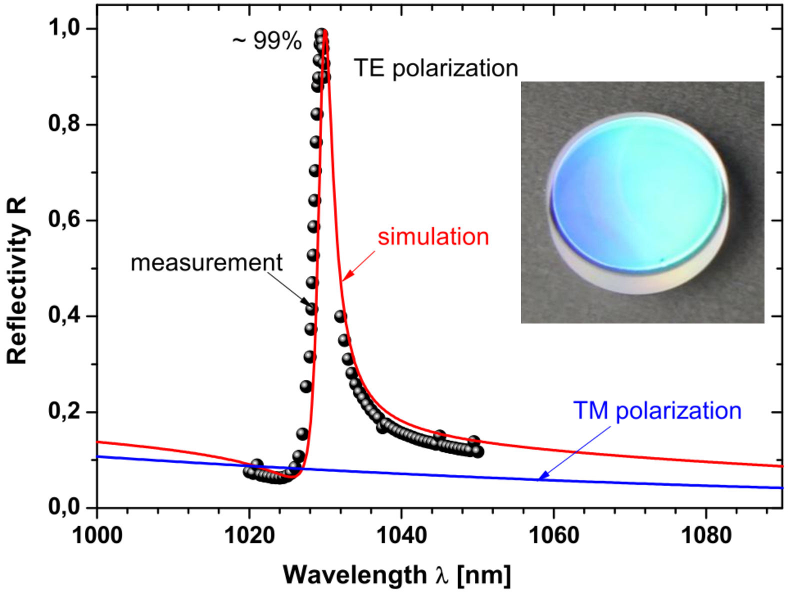
  - Coupling condition
    - $\beta = k_{inc} + K_g$ i.e.
    - $N_{eff} = \sin\theta + m*\lambda/\Lambda$

*A. Avrutsky and V.A. Sychugov, Journal of Modern Optics, 36(11), 1527-1539 (1989)

Applications in high-power lasers

- Polarization and wavelength selective GWS: narrow bandwidth and linearly polarized thin-disk laser (**beneficial for SHG**)
- Resonant grating mirror: Single-layer corrugated waveguide
- **300 nm Ta_2O_5** film (Ta_2O_5) on fused silica substrate
- 50 nm binary grating etched from top





- Measured reflectivity at 1030 nm: **99%**
- Maximum power extracted: **70 W,** Optical efficiency: **24.3%** (M^2 ~ 1.1)
- Laser emission bandwidth (FWHM): **25 pm** (~ 9 GHz)
- Degree of linear polarization: **> 99%**

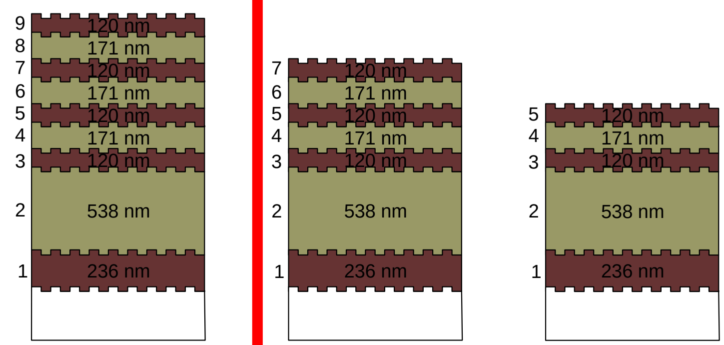
→ Loss still high

M. Vogel, M. Rumpel, et al., Optics Express, 20(4), 4024-4031 (2012)

Applications in high-power lasers

- Polarization and wavelength selective GWS: narrow bandwidth and linearly polarized thin-disk laser (**beneficial for SHG**)
- Combination of partial reflector and GWS

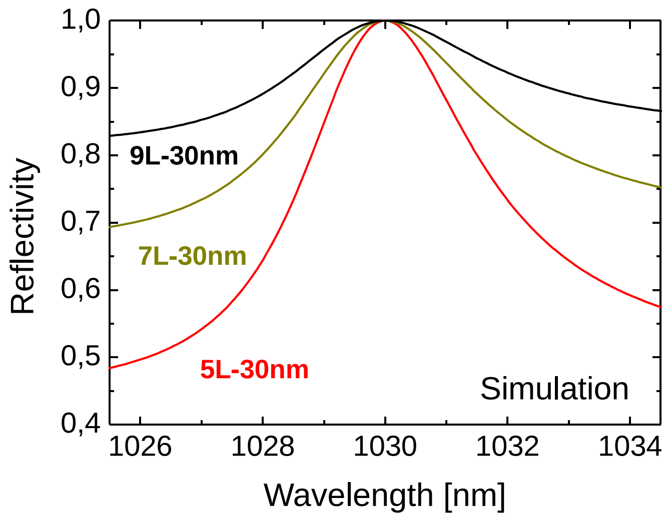
  (PR=uarter-wave layers sequence)
- GWS was designed to operate at an AOI~10°
- Measurement of reflectivity @ AOI~10°
  - 9L-30nm: R_{TE} = 99.9%
  - 7L-30nm: R_{TE} = 99.7%
  - 5L-30nm: R_{TE} = 99.6%

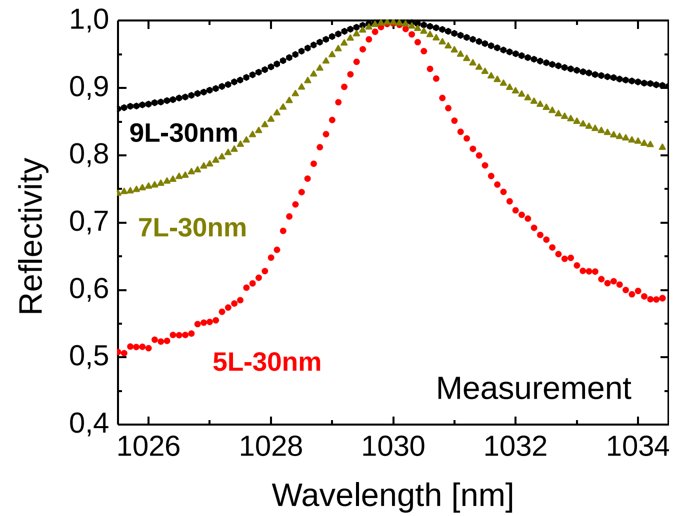


9-layer design, 30 nm grating depth

7-layer design, 30 nm grating depth

5-layer design, 30 nm grating depth

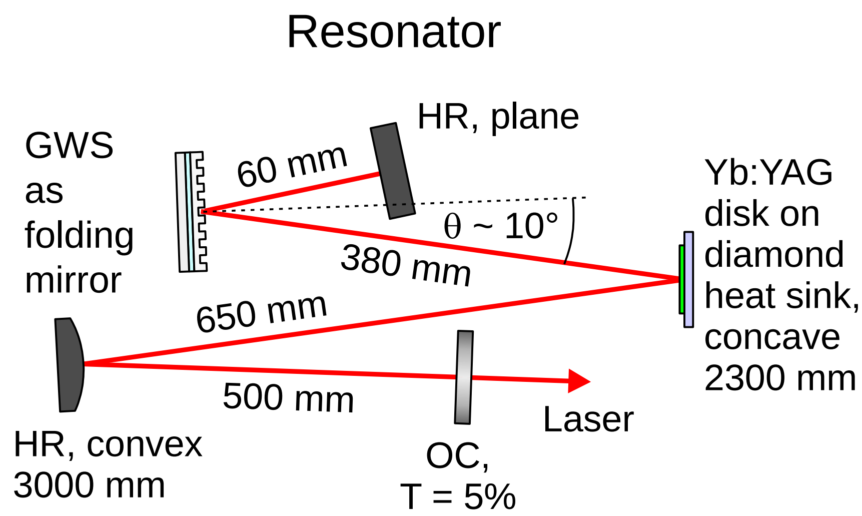


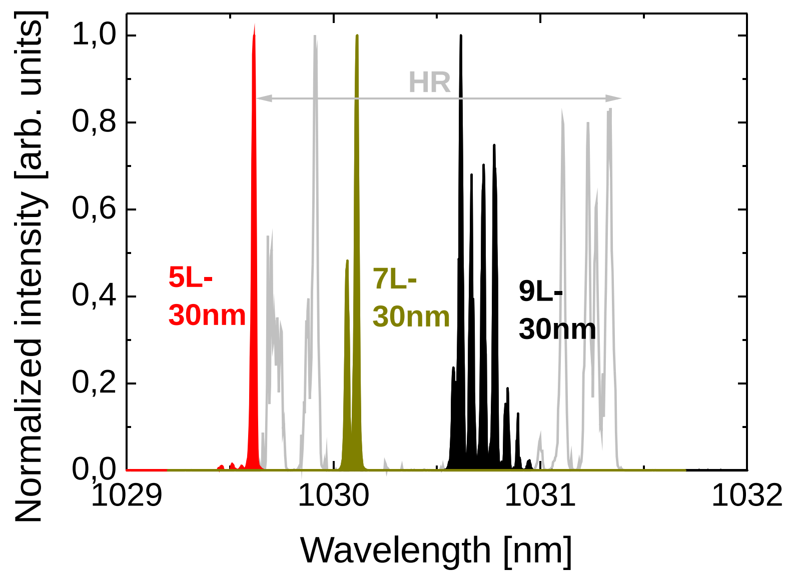


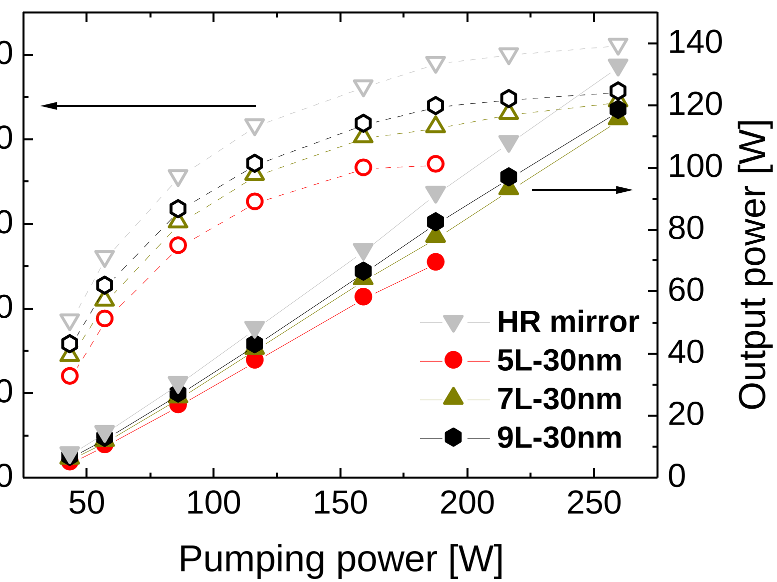
- Measurement accuracy ≈ 0.2%

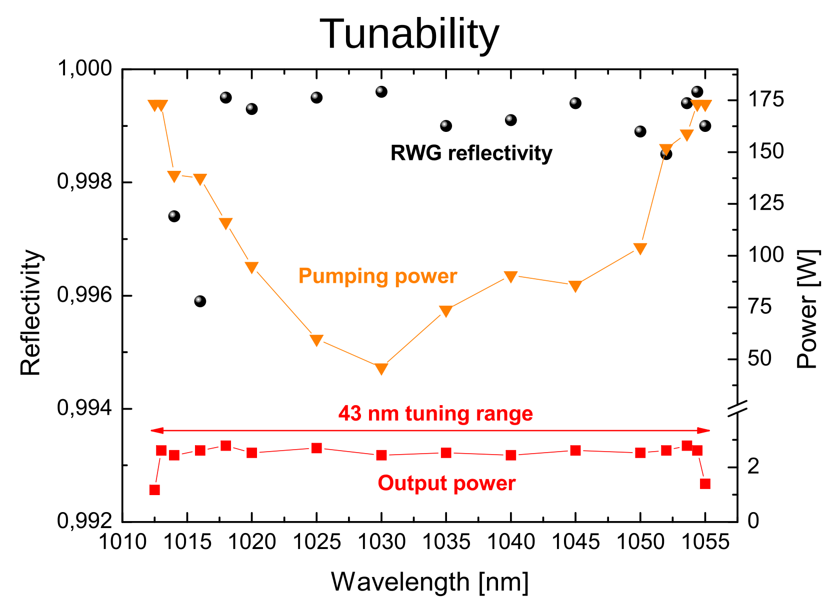
Applications in high-power lasers

- Implementation in high-power **CW fundamental mode** thin-disk laser



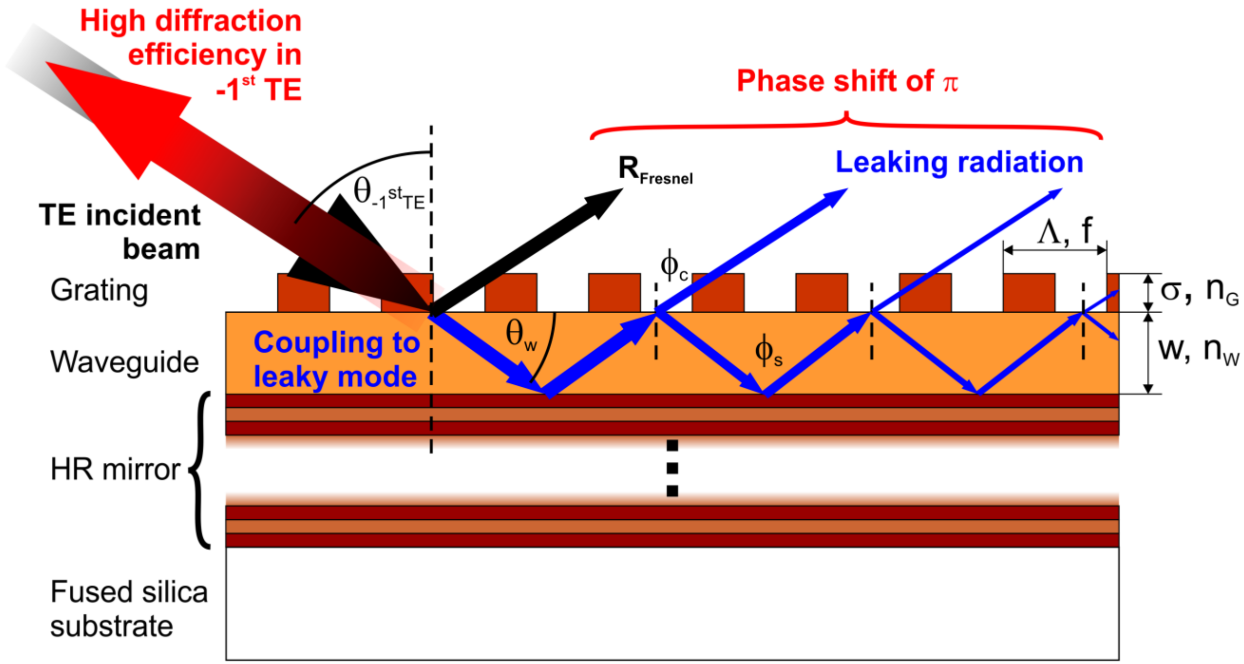






Applications in high-power lasers

- Polarization and wavelength selective GWS: narrow bandwidth and linearly polarized thin-disk laser (**beneficial for SHG**)
- The resonant diffraction effect*

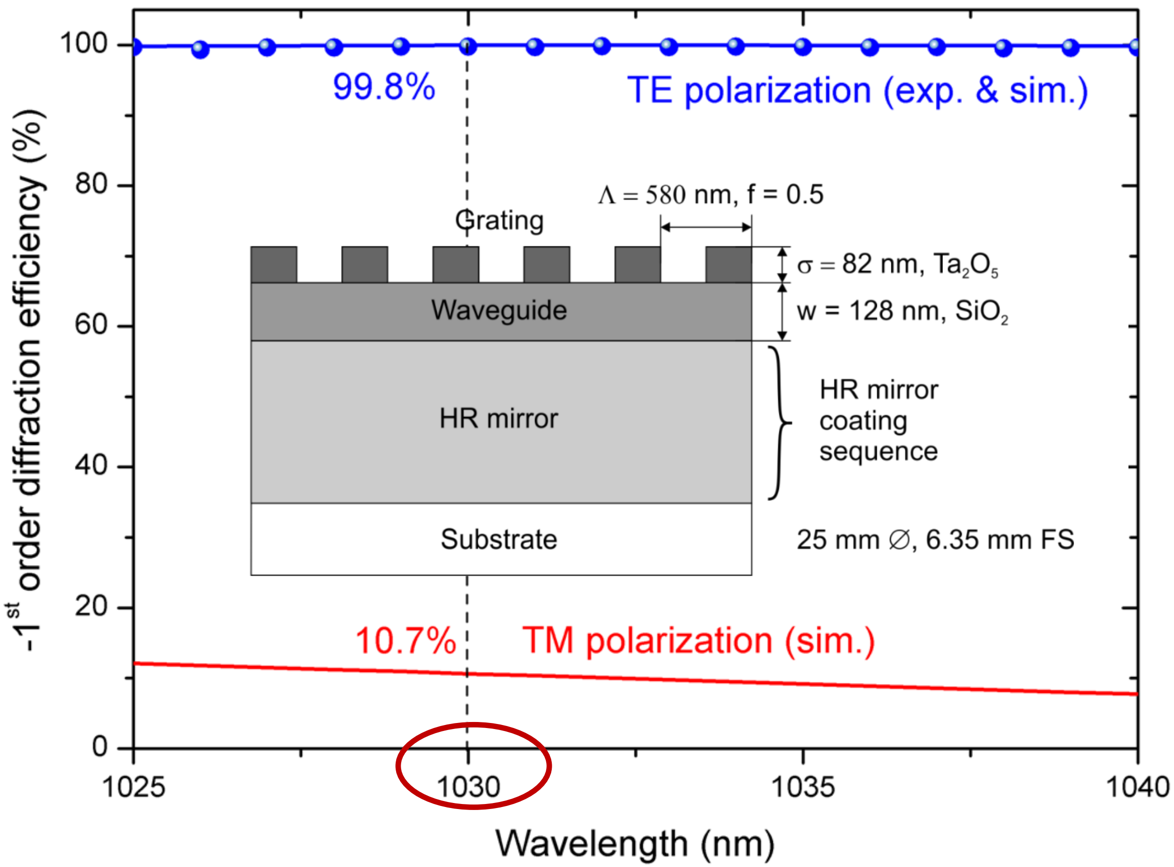


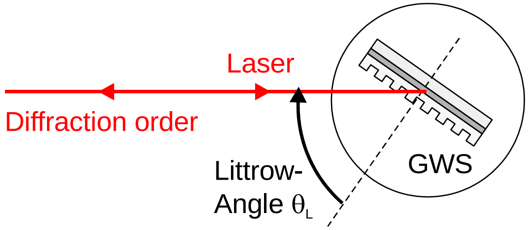
- Grazing incidence: Coupling of leaky modes
- Grating: phase-shift $R_{Fresnel}$ ←→ R_{Leaky}
- Grating: -1st diffraction order in reflection
- All power directed to -1st diffraction order

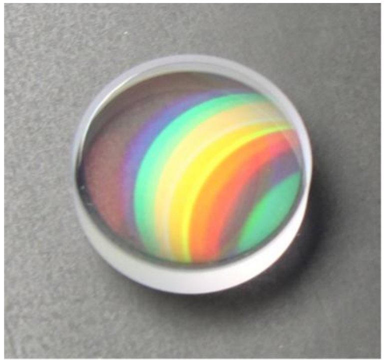
*N. Destouches, M. Abdou Ahmed, et al., Opt. Express 13, 3230-3235 (2005)

Applications in high-power lasers

- The resonant diffraction effect:
  - Design and spectroscopic characterization (meas. diffraction efficiency)
  - High efficiency (99.8% measured) in the -1st order under Littrow angle



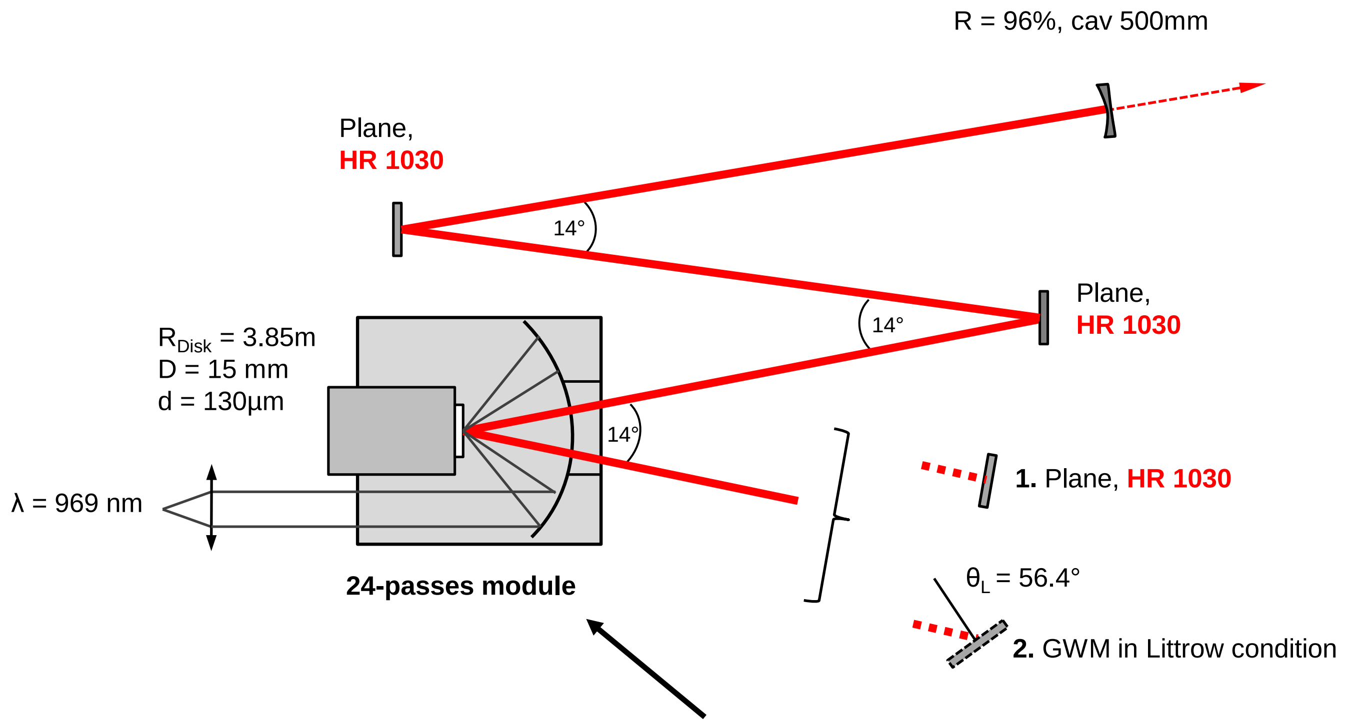




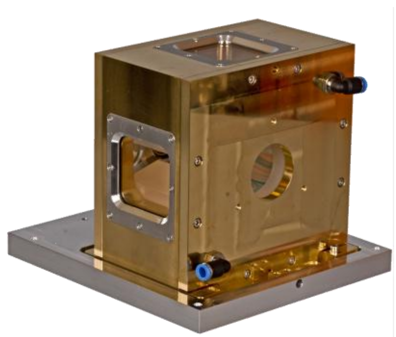
M. Rumpel et al., *Optics letters 37(20), 4188-4190, 2012*

Applications in high-power lasers

- Implementation in high-power **CW fundamental mode** thin-disk laser (**IR**)

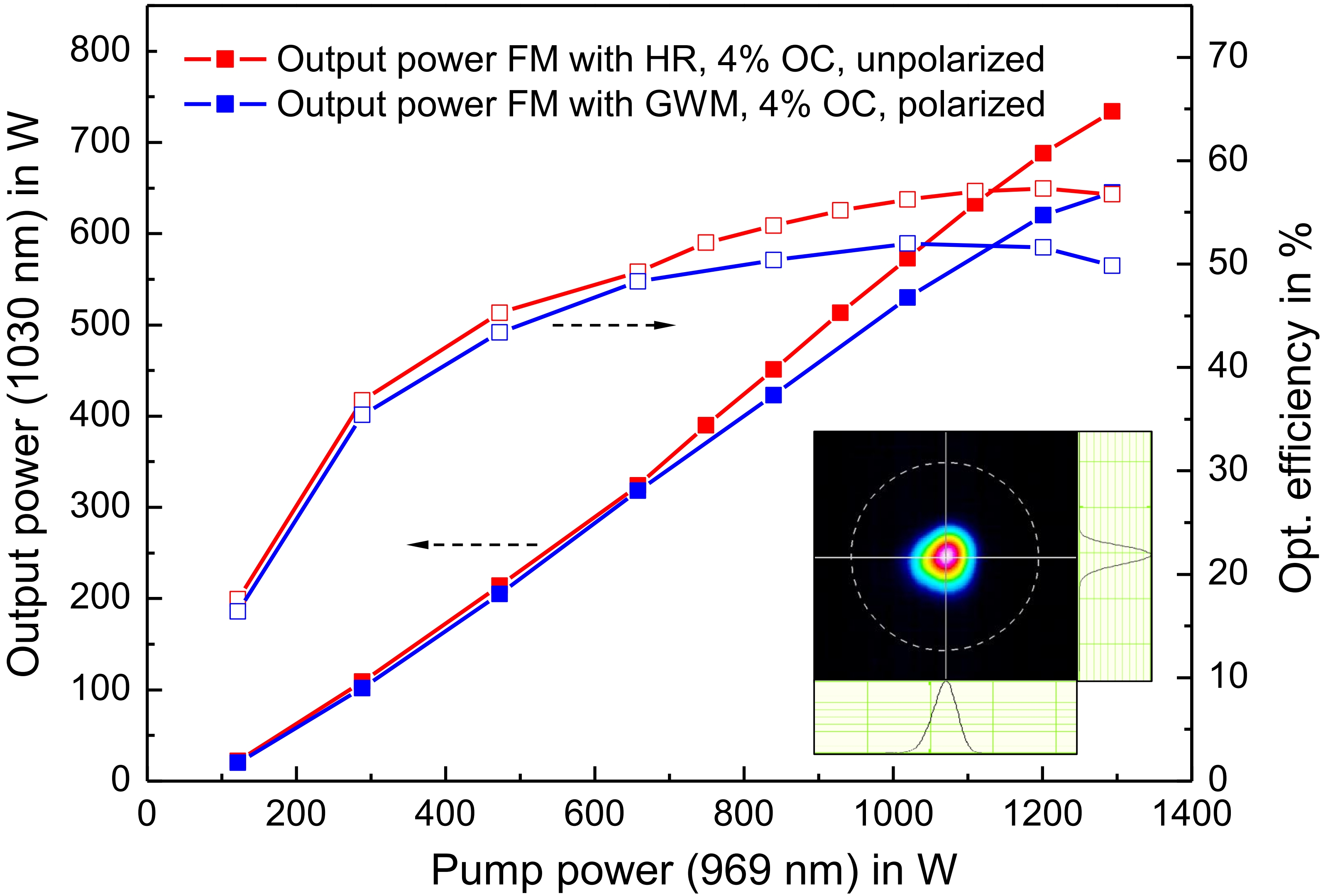


- Pump spot diameter = 5.5 mm
- Total resonator length = 2.1m
- Pumping wavelength: 969 nm



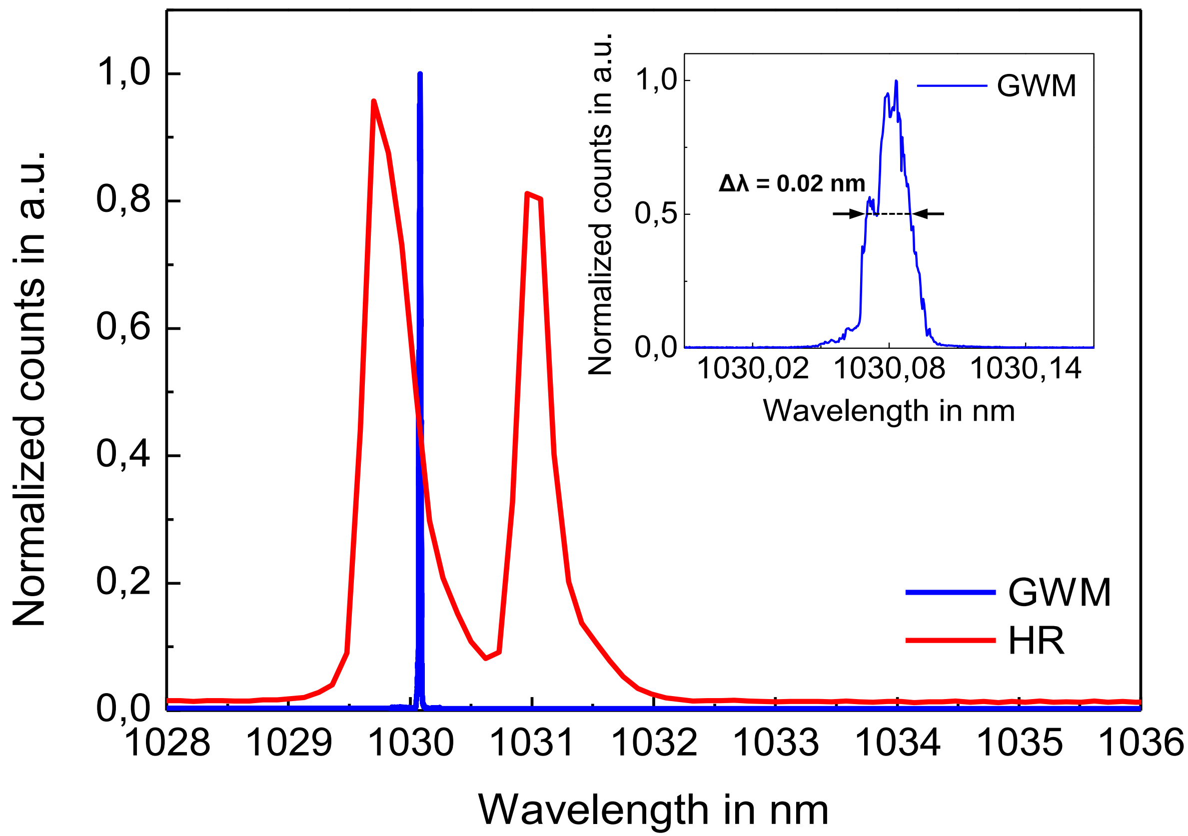
Applications in high-power lasers

- High-power **CW fundamental mode** thin-disk laser (**IR**)
- **Grating: 620W Output** @ 1.2kW Pump, **η_{opt} ~ 51.6 %, M^2_x = 1.33 ; M^2_y = 1.22**



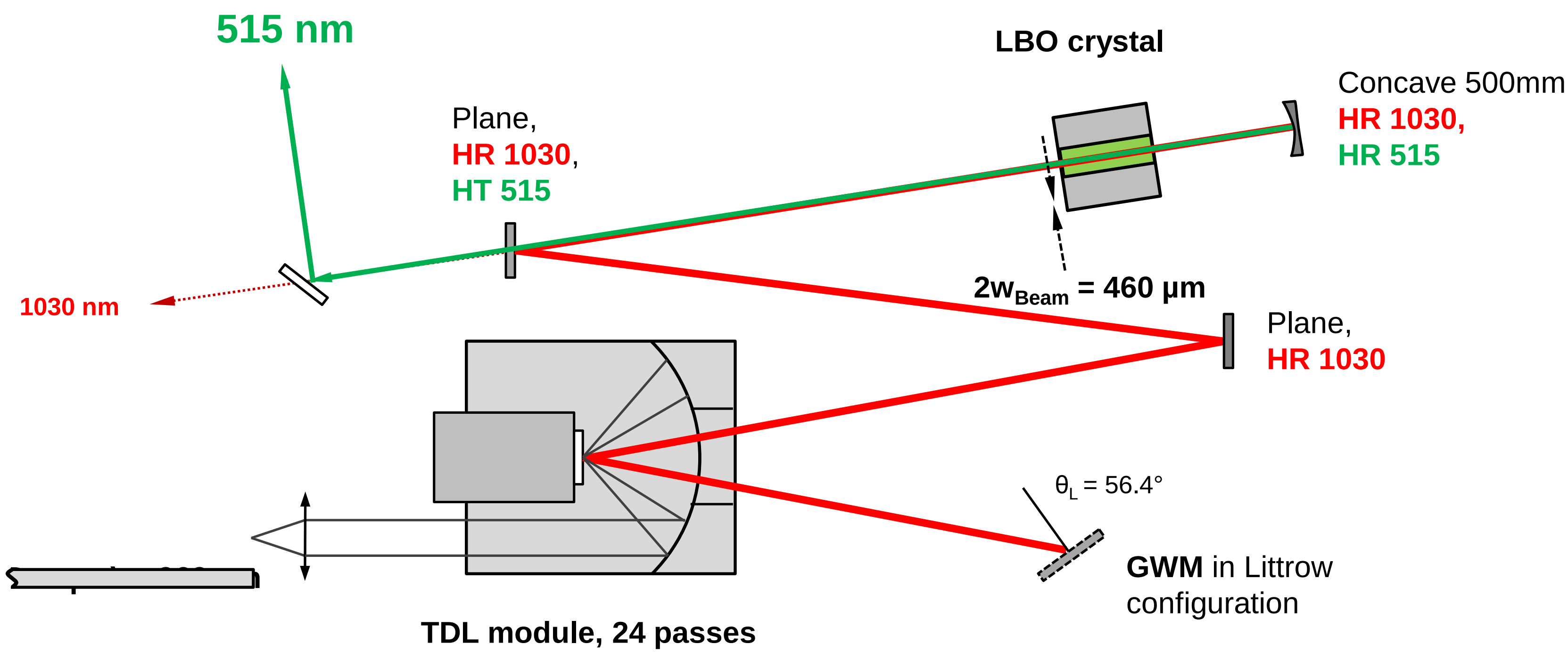
Applications in high-power lasers

- High-power **<u>CW fundamental mode</u>** thin-disk laser (**IR**)
- Laser emission spectra (HR/ GWM: **M^2 < 1.3**)
- **> 200 kW/cm²** CW intra-cavity power density on grating mirror surface at **620 W** output power and 4% OC transmission (15.5 kW intra-cavity power)
- Measured **DOLP > 99.8%**

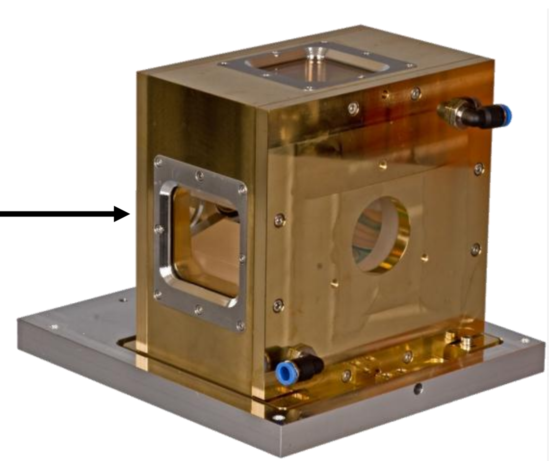


Applications in high-power lasers

- High-power **CW fundamental mode** thin-disk laser (**SHG – Green**)

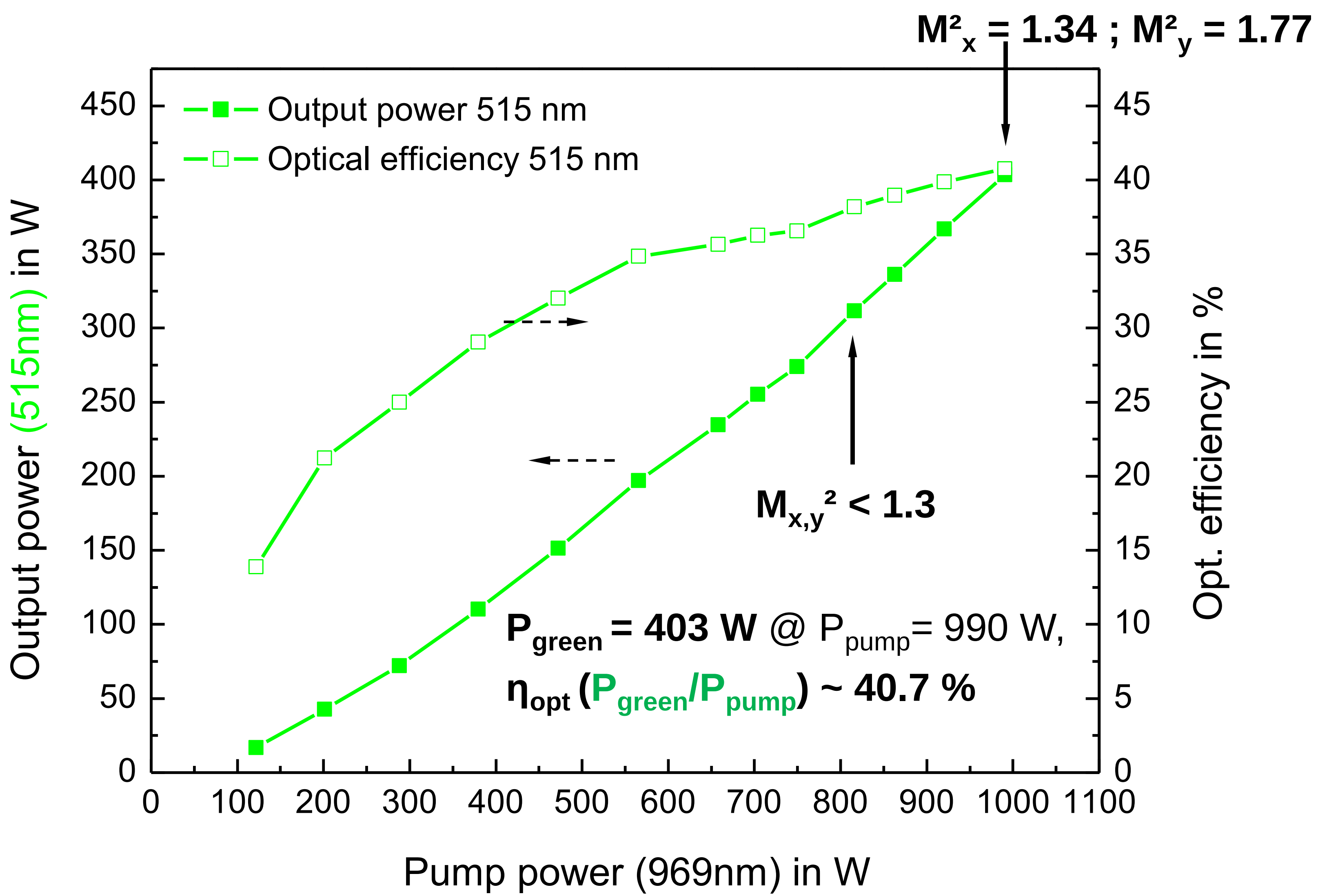


- Pump spot diameter = 5.5 mm
- Total resonator length = 2.1 m
- Pumping wavelength: 969 nm
- LBO: Type I (CPM), (4x4x15) mm³
- Beam diameter in the LBO: 460 µm



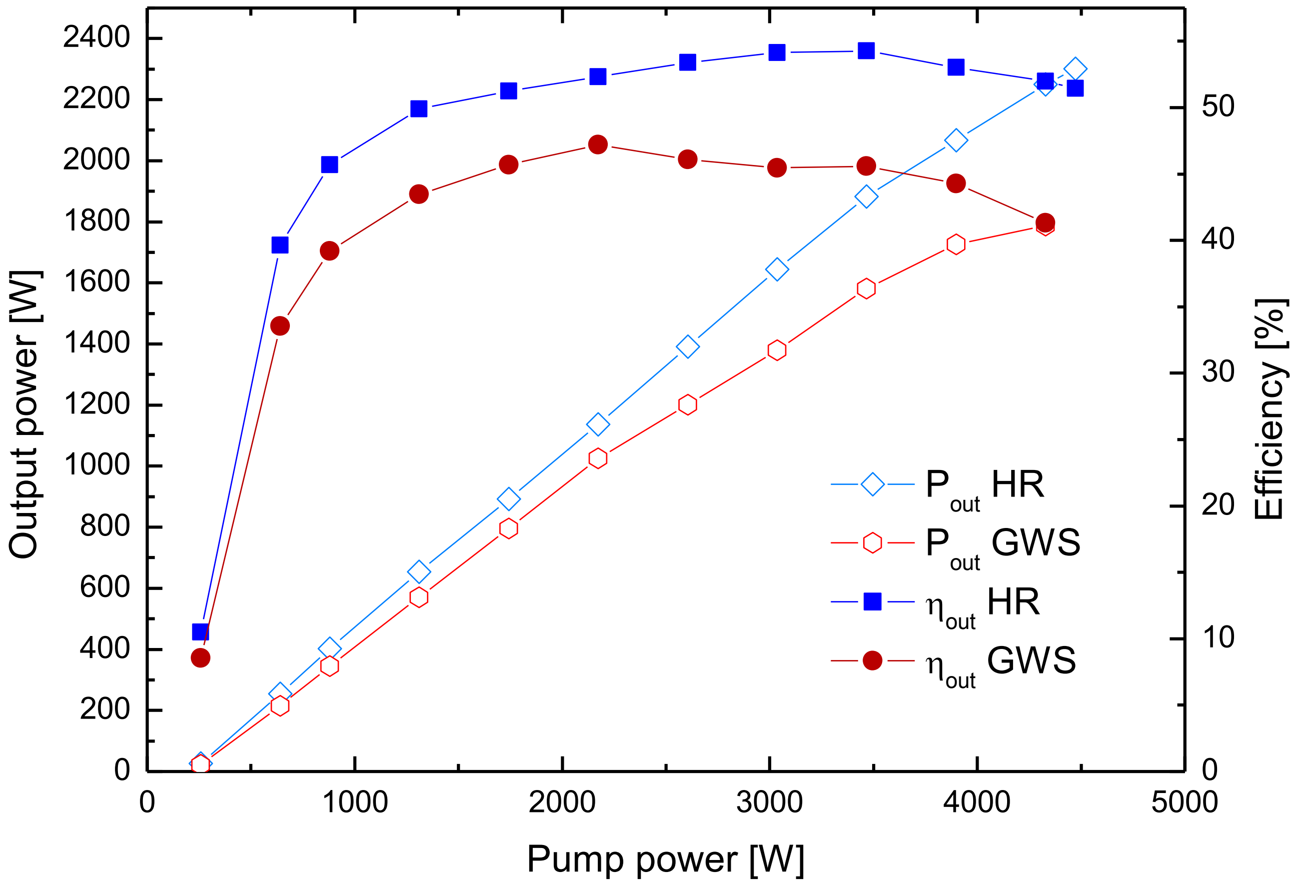
Applications in high-power lasers

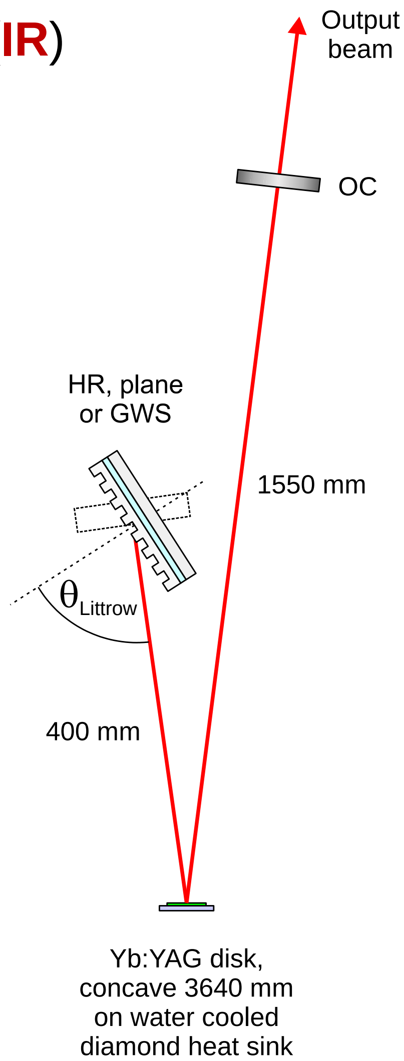
- High-power **CW fundamental mode** thin-disk laser (**SHG – Green**)



Applications in high-power lasers

- Implementation in high-power **CW multimode** thin-disk laser (**IR**)
  - Qualification tests at very high-power



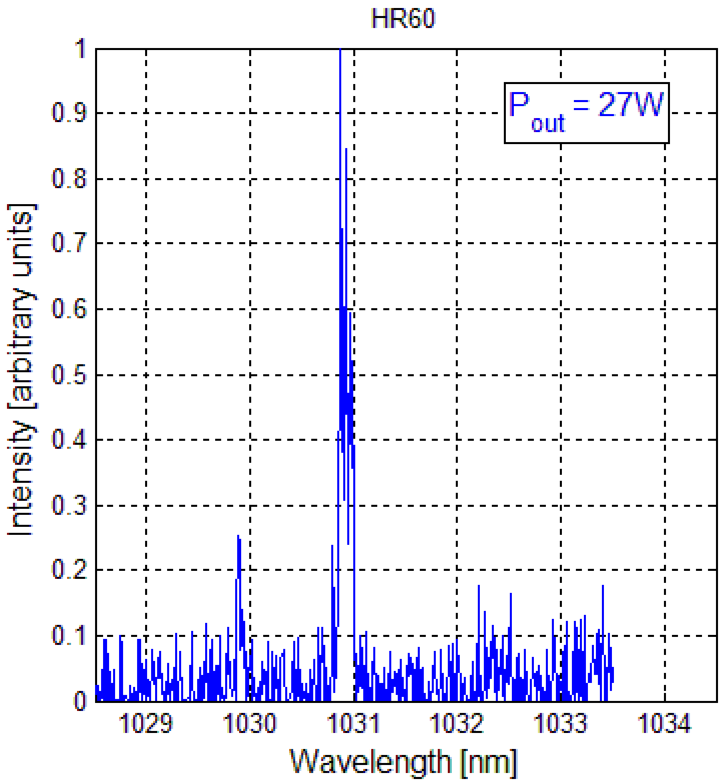


- Up to **1788W** (>125kW/cm²) reached without damage of the grating!

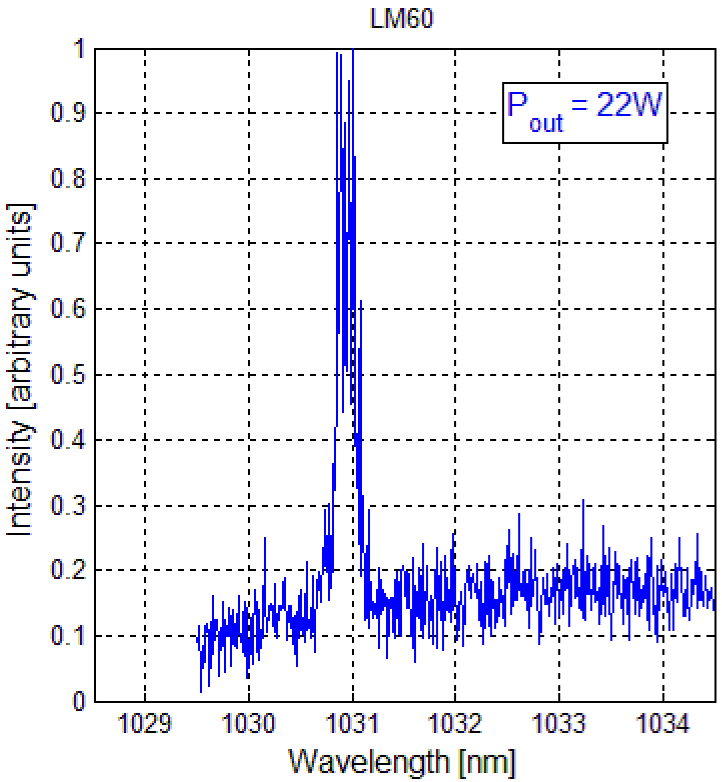
Applications in high-power lasers

Laser emission spectra for HR and GWS

HR



- GWS



→ Wavelength selection + stabilization with intra-cavity GWS

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Summary

Conclusion

- GWS enables the generation of high-power beams with radial polarization
- High-power fundamental mode and multimode SHG in thin-disk laser demonstrated using a GWS as polarization and wavelength selective device
  - GWS enables efficiency increase when compared to standard approaches (etalon, TFP)
  - **TEM_{00}: P_{515nm} = 403 W → 40.7% opt. efficiency**
  - **MM: P_{515nm} = 1080 W → 39.5% opt. efficiency**

Outlook

- LIDT experiments
- Further power scaling **(green)** TEM_{00} > 1 kW & > 2 kW in MM operation

Acknowledgment

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Bundesministerium
für Wirtschaft
und Energie

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Thank you for your attention