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Research Article

Marwan Abdou Ahmed*, Martin Rumpel, Andreas Voss and Thomas Graf

Applications of sub-wavelength grating mirrors in high-power lasers

Abstract: A grating waveguide mirror (GWM) results from the combination of a waveguide and a sub-wavelength grating which lead, for given incidence conditions, to polarization and or wavelength filtering. In the present paper, we report on the application of such elements for the selection of the polarization (linear, radial, or azimuthal) as well as the narrowing, stabilizing and tuning of the emission spectrum of high-power lasers. Using a leaky-mode circular GWM, beams with radial and azimuthal polarization with output powers of up to 275 W and 145 W, respectively, could be extracted from a Yb:YAG thin-disk with optical efficiencies of 52.5% and 43%, respectively. In both cases, the GWM was composed of a highly reflective (HR) mirror and a sub-wavelength grating as the end-mirror of the resonator. Using a leaky-mode linear GWM operating under Littrow condition, beams with linear polarization and a narrow spectral bandwidth were obtained from a Yb:YAG thin-disk laser. In multimode operation, an output power of 325 W was achieved at an optical efficiency of 53.5%. In near-fundamental mode operation, 110 W was extracted at an optical efficiency of 36.2%. In this latter case, the spectral bandwidth was measured to be around 25 pm. Moreover, continuous wavelength tuning from 1007 to 1053 nm was demonstrated with our device.

Keywords: diffraction gratings; laser ytterbium; polarization selective device; sub-wavelength structure; wavelength filtering devices.

OCIS codes: 050.1950; 140.3615; 130.5440; 050.6624; 230.7408.

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1 Introduction

Combining sub-wavelength gratings with planar (single or multi-layer) waveguides is known to exhibit very interesting and specific properties [1–3] which make such structures attractive for many applications in the field of optics, laser physics, and biochemistry [4, 5]. This is due to their unique resonance properties either in reflection or transmission which can be designed for a given polarization, wavelength, and angle of incidence. The sub-wavelength structures can be defined in one or more layers of the optical waveguide. In the past 30 years, the work of several scientific groups [1–3] led to a deep phenomenological and theoretical understanding of the physical behavior of these structures with many applications in different fields such as telecommunications [6], biology [7, 8], and lasers [9].

In the present paper, we illustrate the potential of sub-wavelength grating-waveguide mirrors (GWMs) developed to select the polarization (linear, radial, and azimuthal polarization states) and the wavelength (with narrow spectral bandwidth) of high-power Yb:YAG thin-disk lasers. The following sections give detailed discussions of design requirements as well as spectroscopic characterization and laser performance of different structures.

2 Generation of beams with radial and azimuthal polarization

The benefits of beams with radial and azimuthal polarization have attracted much interest in the past few years. For instance, radially polarized beams are advantageous for particle acceleration [10], particle trapping or guiding [11], lithography, data storage, resolution-enhanced microscopy [12], orientation of single molecules, and for optical tweezers [13]. At high powers, the most interesting application is metal processing such as metal sheet cutting [14] or welding [14], as well as drilling [15]. During the past 30 years different extra- and intra-cavity approaches for the generation of radially and azimuthally polarized beams have been developed and reported by several scientific groups [16–20].

To generate radially or azimuthally polarized beams, polarization-selective GWMs with a leakage for undesired polarization states can be used as the end-mirror of a laser resonator. As discussed in the following, this is also applicable to Yb:YAG thin-disk lasers despite the comparatively high intra-cavity intensities. The structure we used here combines a sub-wavelength grating and a fully dielectric multilayer which acts both as a conventional HR mirror and a planar waveguide. Using a fully dielectric structure has the advantage to be very suitable for high-power applications.

As can be seen in Figure 1, the grating was etched into the substrate and is therefore replicated throughout the whole multilayer which was coated on top. This multiple corrugation enhances coupling efficiency of the grating and allows reducing the required etching depth, which is important to minimize scattering losses and to widen manufacturing tolerances.

The intra-cavity polarizing effect is introduced by a difference of reflectivity for the two orthogonal polarization states which is achieved by selectively coupling the incident free-space beam to one (or two neighboring) leaky-modes of the wave-guide in the multilayer mirror [21–23]. For intra-cavity generation of a linearly polarized beam, grating lines would be straight. To generate azimuthal or radial polarization states, grating lines are circular.

Grating-induced coupling of incident free-space radiation to waveguide modes is polarization-selective because the phase matching (or resonance) condition [24] can only be fulfilled for one polarization at a time for a given angle of incidence and wavelength. The coupling condition is expressed by the following relation:

$$n_{eff} = \sin\theta \pm m\frac{\lambda}{\Lambda}$$

where n_{eff} is the (polarization-dependent) effective refractive index of the waveguide mode, θ is the angle of incidence of the free-space beam, m is the diffraction order, λ is the wavelength of the incident beam, and Λ is the period of sub-wavelength grating. If the incident free-space beam is thus coupled to a leaky-waveguide mode of the dielectric multilayer it experiences a reduced reflectivity at the mirror which can be exploited for polarization discrimination in a laser resonator. Indeed, grating inherently also leads to a power leakage from the waveguide mode through the ± 1st diffraction order into the substrate as depicted in Figure 1 [21–23]. The same concept has also been demonstrated for high-power CO_2 laser [21].

To apply the above described concept to a Yb:YAG thin-disk laser, we have chosen a standard HR multilayer mirror composed of 29 alternating Ta_2O_5/SiO_2 quarter-wave layers coated on fused silica substrates. At a wavelength of 1030 nm the nominal refractive indices n (as communicated by the supplier) and thicknesses w of the layers are n_h=2.185 and w_h=118 nm for Ta_2O_5 and n_l=1.48 and w_l=174 nm for SiO_2. Two sub-wavelength grating designs were applied for the selection of beams with radial (GWM-1) and azimuthal (GWM-2) polarization, respectively. In the first case, a grating with a period of Λ=930 nm and a groove depth of σ=15 nm was designed and fabricated, whereas in the second case a period of Λ=1000 nm and a groove depth of σ=110 nm was chosen. Figure 2 shows calculated and measured spectra of reflectivities of two GWMs.

At Yb:YAG laser wavelength of λ=1030 nm, measured and calculated reflectivities for azimuthal and radial polarizations are summarized in Table 1.

In both cases, measurements are in good agreement with modeling results (also shown in Figure 2) and demonstrate high reliability of our polarizing scheme.

The above GWMs were used as the end-mirror of a 1.35-m long V-shaped thin-disk laser resonator. The 215-µm thick Yb:YAG thin-disk was pumped in a spot with a

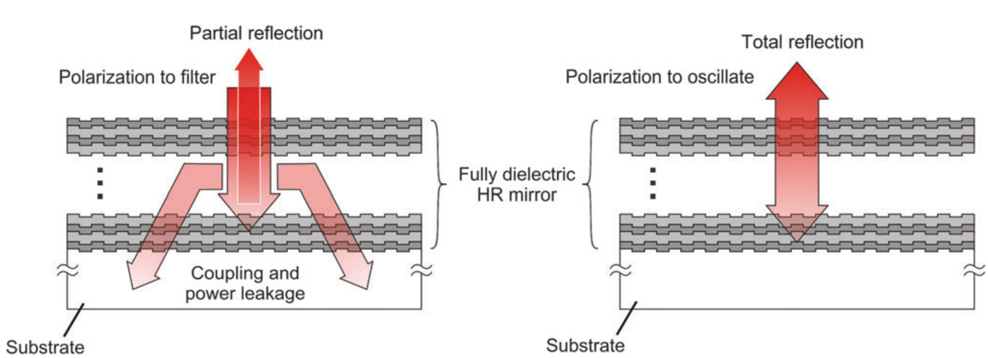

Figure 1 Schematic of the polarizing mechanism based on a leaky-mode grating waveguide mirror (GWM).

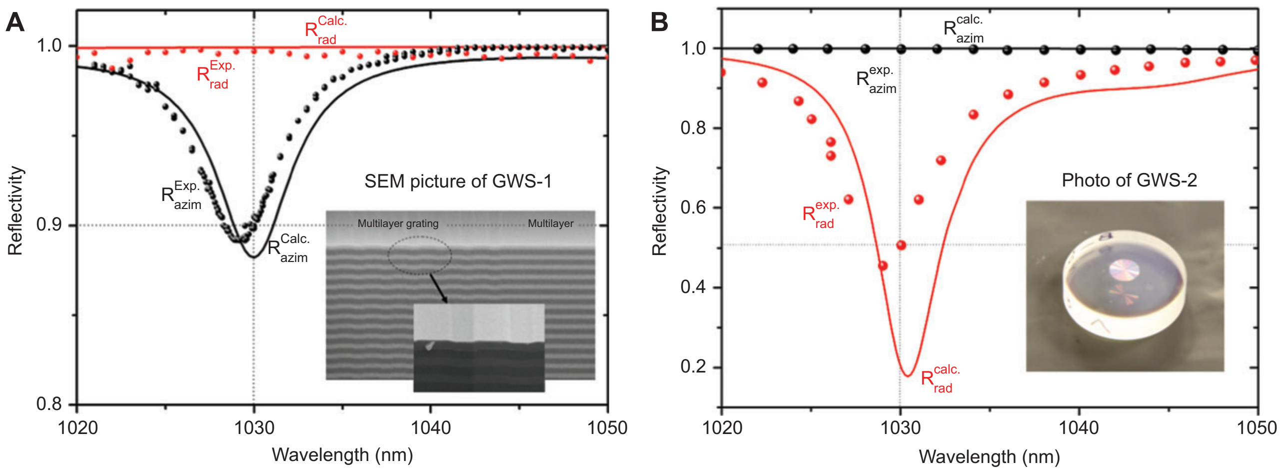

Figure 2 Calculated (solid lines) and measured (dots) reflectivities of the fully dielectric mirror with a grating with period of Λ=930 nm and a groove depth of σ=15 nm (GWM-1) (A) and a grating with a period of Λ=1000 nm and a groove depth of σ=110 nm (GWM-2) (B).

diameter of 3.6 mm by a fiber-coupled pump diode with up to 525 W of power at a wavelength of 941 nm using a standard thin-disk pumping module as commercially available from the Institut für Strahlwerkzeuge (IFSW). The curvature of the disk was measured to be ≈4 m at room temperature. The transmission of the plane output coupler was 4%. The resonator setup was designed for the TEM_{01}*-mode with M^2≈2 to match the pump spot diameter on the disk at full power.

With GWM-1 a radially polarized output power of up to 275 W was generated with an excellent optical-to-optical efficiency of 52.5%. The beam propagation factor was measured to be M^2≈2.3, which is consistent with the theoretical value of the fundamental doughnut mode. An output of up to 145 W of azimuthally polarized laser radiation with M^2≈2.4 and an optical-to-optical efficiency of 43% were measured using GWM-2.

In comparison with results obtained with a standard HR end-mirror instead of GWMs, efficiency was found to be slightly reduced by 7% with GSM-1 and by 10% with GWS-2. As expected, the beam quality factor of the laser beam generated with the HR mirror was unchanged and was measured to be M^2≈2.4 again at full power. Additional losses introduced by the GWM are attributed to several causes:

	Radial polarization	Azimuthal polarization
GWM-1	$R^{calc.}$=99.92%	$R^{calc.}$=88.83%
	$R^{meas.}$=(99.8±0.2)%	$R^{meas.}$=(90±0.2)%
GWM-2	$R^{calc.}$=21.45%	$R^{calc.}$=99.95%
	$R^{meas.}$=(54±0.2)%	$R^{meas.}$=(99.7±0.2)%

Table 1 Calculated and measured reflectivities at 1030 nm wavelength for GWM-1 and GWM-2.

– Maximum reflectivity of the GWM for the desired polarization is still 0.1–0.3% lower than that of a conventional HR mirror.
– Residual stress caused by soldering of the thin disk onto the heat sink and thermally induced stress during the operation may lead to stress-induced birefringence causing depolarization losses.
– Intensity distribution of pure doughnut mode (with vanishing intensity in the center) generated in radial or azimuthal polarization has a smaller spatial overlap with the pump spot on the disk than the multi-mode beam with a more even intensity distribution generated with the HR mirror.

Figure 3A,B shows intensity distributions of radially and azimuthally polarized beams (top left) as well as their analysis by transmission through a linear polarizer with different orientations. Degree of polarization was measured to be higher than 98±0.5% (Figure 3C,D) with a homemade 2D-polarimeter [23, 25], revealing a high purity of radial and azimuthal polarization of the beams generated with our GWMs.

Further improvements could be achieved by using a mirror which combines a high-index substrate, for example, YAG or Sapphire, for a better heat conductivity and a slightly modified multilayer. According to our simulations this will lead to a more tolerant polarizing device with a nearly unaffected reflectivity for lasing polarization. A further improvement could be achieved by using a thinner laser crystal to minimize depolarization losses as well as a ring-shaped pump profile to achieve a better spatial overlap between laser mode and pumping intensity distribution.

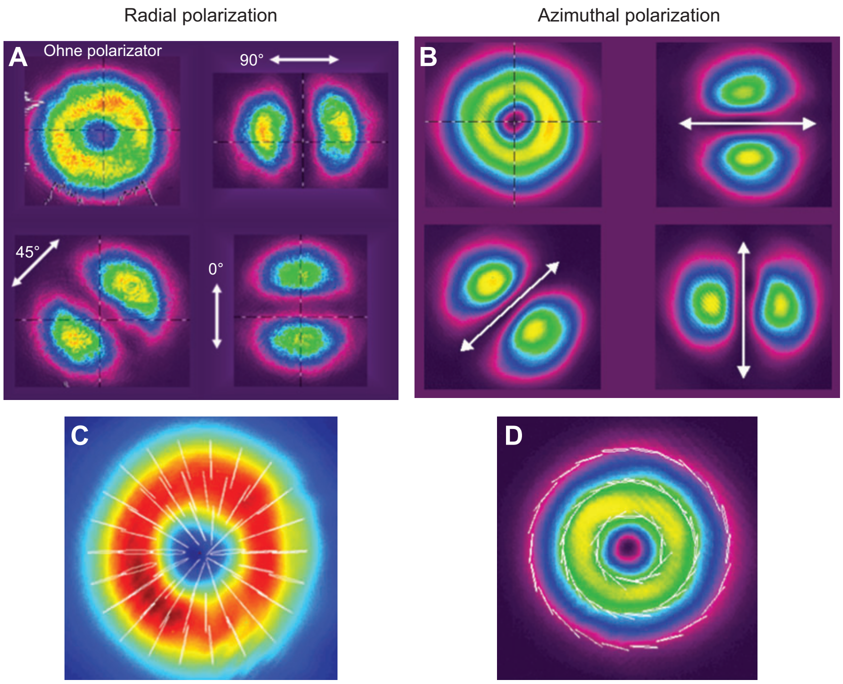

Figure 3 Polarization analysis of radially (A and C) and azimuthally (B and D) polarized laser beams generated by GWMs in the thin-disk laser.

3 Generation of linearly polarized beams with narrow spectral line width

As mentioned above, sub-wavelength grating waveguide mirrors are also inherently wavelength selective. This property is particularly attractive for applications with high-average powers where transmissive elements such as etalons and Lyot filters are limited by thermal lensing. Generation of linearly polarized radiation with a narrow spectral linewidth is a prerequisite, for instance, for intracavity second harmonic generation.

The structure that we developed for tuneable and narrow-band wavelength selection in high-power thin-disk laser resonators is a combination of an HR mirror, a leaky-waveguide on top of this, and a linear sub-wavelength diffraction grating, similar to the one described in [26, 27].

The operating principle is schematically summarized in Figure 4. The structure is composed of a fused silica substrate, a Ta_2O_5/SiO_2 multilayer mirror, a 123-nm thick leaky-waveguide layer, and a grating with a period of 580 nm fully etched in an 82-nm thick Ta_2O_5 layer.

A free space incident wave directed to the GWM under angle θ_i can excite a leaky-mode if the coupling condition $k_0 n_w w\cos(\theta_w)+\frac{\varphi_c+\varphi_s}{2}=m\pi$ is fulfilled. Here, k_0 is the vacuum wave number $\left(k_0=\frac{2\pi}{\lambda}\right)$, n_w the refractive index of the waveguide layer of thickness w, θ_w the angle in the waveguide laser, φ_c and φ_s are the reflection phase shifts on the boundaries between waveguide and grating and between waveguide and HR mirror, respectively, and m is an integer. The mode propagating in the waveguide layer is designed to be lossy and therefore is re-radiated out of the waveguide layer after a certain propagation length. Due to the HR mirror below the leaky-mode waveguide (SiO_2 layer), this structure has a reflectivity of almost 100% in the 0th order. Adding diffraction grating introduces the -1st diffraction order in reflection as an additional port (which has to be the only diffraction order present for the desired operating region). Additionally, the presence of grating can modify the phase between the Fresnel reflection part of the incident beam and the coupled and leaking radiation. With a proper design of the optogeometrical parameters of the structure, a completely destructive interference between these two components can be reached for a given polarization, wavelength, and angle of incidence. In this condition, the incident beam will be completely directed to the -1st order of diffraction. Hence, the GWM can be used as end-mirror in a laser cavity under Littrow configuration (i.e., the diffracted beam and the

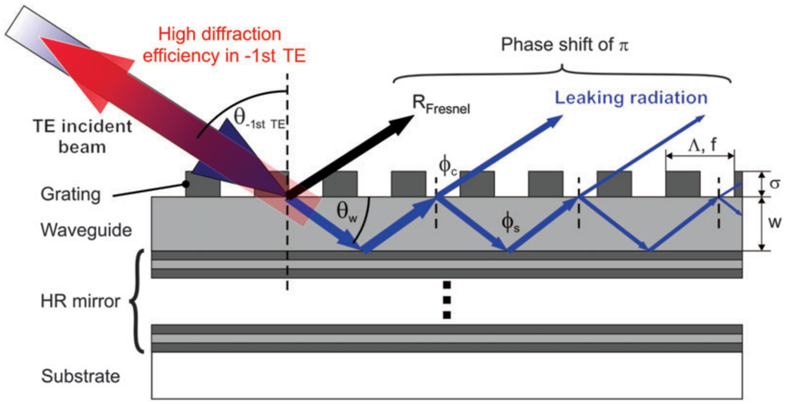

Figure 4 Scheme of the linearly polarizing and wavelength selective GWM under Littrow incidence. The structure is composed of a fused silica substrate, a Ta_2O_5/SiO_2 multilayer mirror, a 123-nm thick leaky-waveguide layer, and a grating with a period of 580 nm and a groove depth of 82 nm.

incident beam are counter-propagating on the same beam axis). Due to the strong dispersion of the -1st order, only a narrow spectral bandwidth is able to oscillate in a typical laser cavity if such a mirror is used under Littrow configuration. Strong dependence of the Littrow angle from the wavelength additionally enables tuning the laser emission wavelength by tilting the intra-cavity GWM. The Littrow configuration has to have high diffraction efficiency over the tuning range to allow efficient wavelength tuning. The polarization-selective properties of the GWM are given by the fact that the phase shifts contributing to the high diffraction efficiency are polarization-dependent.

For an experimental demonstration a grating with a period Λ of 580 nm and a groove depth σ of 82 nm was designed and fabricated [28]. It was combined with a quarter-wave multilayer HR mirror operating at an angle of incidence of approximately 62–63°.

Calculated (straight lines) and measured (spheres) diffraction efficiencies in the -1st order for both transverse electric (TE) and transverse magnetic (TM) polarization are shown in Figure 5.

At 1030 nm, a -1st order diffraction efficiency of 99.6±0.2% was measured for TE polarization whereas it was measured to be only around 17% for TM polarization. The slight deviation between the simulation (99.9% efficiency for TE polarization) and the experiment results is mainly attributed to a somewhat higher etching depth of grating than intended.

A scanning electron microscope (SEM) picture of a fabricated GWM from the same type is shown in the inset of Figure 5. The performance of the GWM was tested with the two resonator setups shown in Figure 6. The multimode V-shaped resonator (shown on the left side) has a total length of ≈1115 mm. The resonator produces a beam with M^2=6–9 using a 3.2-mm pump spot diameter on the disk. The resonator has a plane output coupler (OC) with a transmission of 4%. The 180-µm thick Yb:YAG disk crystal with a radius of curvature of 2 m was glued on a water cooled diamond heat sink to attain an efficient heat extraction. The thin-disk laser crystal was pumped with a standard 24-passes IFSW pumping module. The GWM was mounted onto a water cooled holder combined with rotary and translation stages, allowing a very precise alignment of the orientation of the grating lines with respect to the resonator beam. The beam diameter on the GWM was 2.9 mm. The fundamental-mode resonator (Figure 6, right) has a length of 1060 mm. A pair of concave and convex folding mirrors (telescope) was added to match the diameter of the fundamental mode to that of the pump spot on the thin-disk crystal. In this fundamental-mode resonator, the beam diameter on the GWM amounts to 3.2 mm.

In multimode operation (M^2=6–9), up to 325 W of output power was extracted from the laser corresponding to

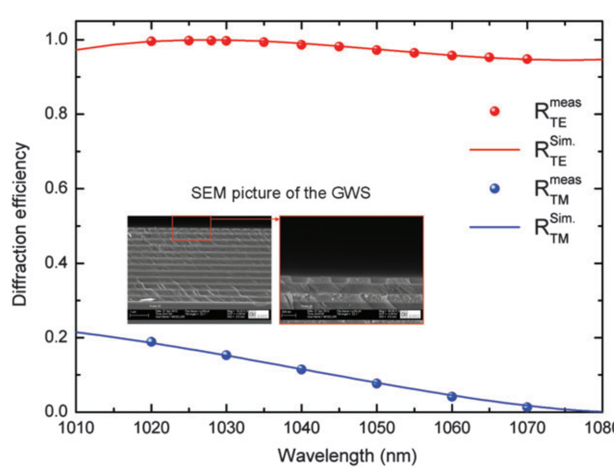

Figure 5 Calculated (solid lines) and measured (dots) diffraction efficiencies for both TE and TM polarization under Littrow incidence.

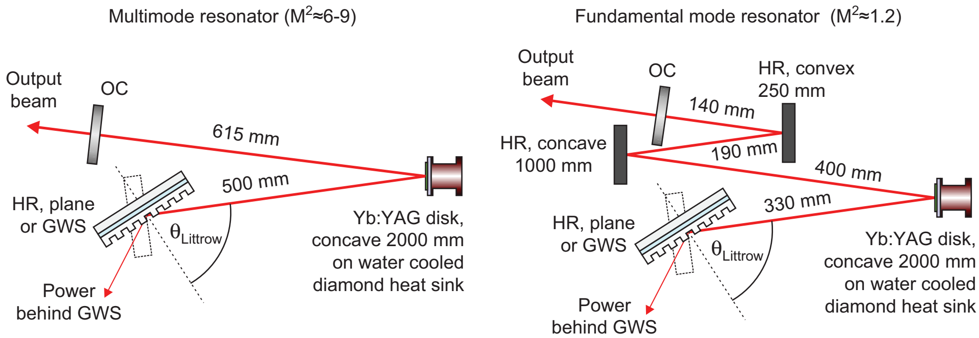

Figure 6 Multimode (A) and fundamental mode (B) resonator for the laser test of the linearly polarizing and wavelength selective GWM.

an optical efficiency of 53.2%. The highest optical efficiency of 55.1% was reached for 260 W of output power. In comparison with a conventional HR mirror, this corresponds to a minor reduction in efficiency of only 6.7%. By taking into account measurements of reflectivity of the GWM, it can be predicted that the same type of element, optimized with its maximum diffraction efficiency centered at 1030 nm, should perform almost as well as a standard HR mirror.

The degree of linear polarization (DOLP) of this laser configuration was measured to be higher than 98.5% over the whole power range and the width of the emission spectrum was reduced from 2.5 nm to 0.7 nm at 325 W of output power. Taking into account the above-mentioned beam diameter, it follows that the GWM was able to tolerate a power density of up to 125 kW/cm^2, which is a notable record for such a device. Additionally, the (surface) temperature of the device which was measured with an IR thermo-camera to be approximately 65°C at full output power (325 W) confirms that the device exhibits a fairly low and acceptable absorption. Further optimization of the element may include the use of thinner substrates with a higher heat conductivity (YAG, Sapphire, or crystalline quartz) and will allow to scale the power into the multi-kW level.

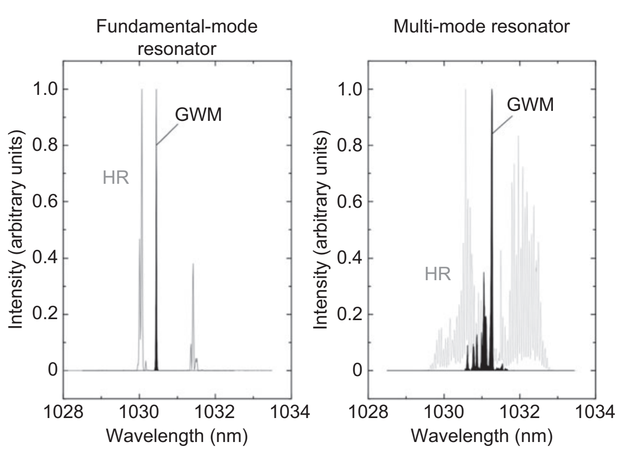

Figure 7 Laser emission spectrum of 110 W in close to fundamental mode (left) and 325 W in multimode (right) with and without the GWM.

With the fundamental mode resonator (M^2≈1.2), an output power of 110 W with an optical efficiency of 36.2% was reached (limited by the stability of the resonator). Compared with a conventional HR end-mirror the reduction of the overall efficiency was again only 7%. The DOLP was again measured to be higher than 98.5% and remained constant over the whole power range. The spectra of the emitted laser beam showed a single peak with a full width half-maximum (FWHM) bandwidth of around 25 pm (limited by the resolution of our optical spectrum analyzer (OSA)).

A comparison of the emission spectra for both resonator configurations with either the GWM or a standard HR mirror is shown in Figure 7. In both cases, the GWM was adjusted to operate at the wavelength at which the highest output power is reached, which was found to be at 1030.5 nm in fundamental-mode operation and 1031 nm in multimode operation.

Wavelength tuning properties were investigated in the multimode resonator with 1% of output coupling and a maximum pump power of 190 W. This corresponds to a power density of 2.4 kW/cm^2 on the disk, which was chosen to avoid damaging the disk even in the case of an interrupted laser oscillation. The GWM exhibited a continuous tuning range from 1007 nm to 1053 nm. The DOLP was measured to be higher than 98.5% over the whole tuning range. Because intra-cavity power is very high at an output coupling of 1% only, in order to prevent damage of the GWM, the pump power was reduced during measurements in spectral regions with strong laser gain.

In this section, we have demonstrated a GWM for highly efficient intra-cavity generation of linearly polarized (DOLP≈98.5%) laser radiation, which additionally allows wavelength selection and tuning. Up to 325 W of output power was extracted from a thin-disk laser in multimode and 110 W in fundamental mode operation with an efficiency of 53.2% and 36.2%, respectively. The slightly higher losses in comparison to a standard HR mirror are attributed to depolarization effects from the disk and to small fabrication imperfections on the GWM. In fundamental-mode operation ($M^2 \approx 1.2$), spectral width of the laser emission is <25 pm. A tuning range from 1007 to 1053 nm was demonstrated. It is therefore possible and believed that using a further optimized GWM, especially having its reflectivity maximum centered to the maximum laser emission at 1030 nm, will allow reaching even better laser performances.

4 Conclusion

In conclusion, we have presented two potential applications which can take benefit from the unique spectral and polarization-selective properties of sub-wavelength grating waveguides. Beams with radial and azimuthal polarization with a beam quality factor M^2 of approximately 2.3–2.4 and powers of up to 275 W (radial) and 145 W (azimuthal) were extracted from a Yb:YAG thin-disk laser. Moreover, the spectral linewidth of a multimode laser was reduced by a factor of 3 at 325 W of output power using a grating waveguide structure operated under Littrow condition. In fundamental-mode operation, up to 110 W of output power with a spectral width of <25 pm was demonstrated with the same device. DOLP was measured to be higher than 98.5% in both laser configurations and over the whole power range. Further experiments of optimized structures are under progress with the objective to generate beams in the multi-kW power range.

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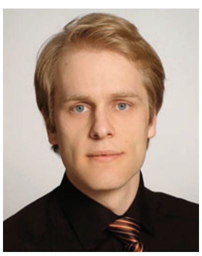
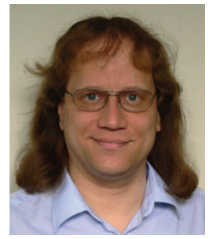


Martin Rumpel received his diploma degree in engineering from the University of Stuttgart, Germany. Since the beginning of 2011, he is working towards a PhD degree, where he is involved in the modeling and spectroscopic characterization, as well as characterization in laser operation of sub-wavelength waveguide grating structures for polarization and frequency selection in solid state lasers, particularly Yb:YAG thin-disk lasers.



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Thomas Graf was born in Switzerland in 1966. He received his physics MSc degree in 1993 and his PhD degree in 1996 from the University of Bern. After 15 months of research at Strathclyde University in Glasgow (UK), he was appointed Head of the High-Power Lasers Group at the Institute of Applied Physics at the University of Bern (in April 1999), where he was awarded a 'venia docendi' in 2001 and was appointed Assistant Professor in April 2002. In June 2004, he was appointed University Professor and Director of the Institut für Strahlwerkzeuge (IFSW) at the University of Stuttgart (D). At the IFSW, Prof. Graf is engaged in high-power laser systems, laser beam shaping, and laser applications in manufacturing. From 2001 to 2007, Prof. Graf served as a board member of the Swiss Society for Optics and Microscopy (SSOM), he is a board member of the European Optical Society (EOS), a board member of Photonics BW e.V., and is a regular member of the German Wissenschaftliche Gesellschaft Lasertechnik e.V., WLT (Scientific Society for Laser Technology).