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Electrically tunable Lyot filter for fast wavelength switching of diode-pumped solid-state disk lasers

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Abstract A new setup for fast wavelength switching of an Yb:YAG disk laser uses a lithium niobate Lyot filter. It is modeled by the Jones matrix formalism and it is tested experimentally. Applying a high voltage to the Lyot filter leads to stepwise wavelength switching of the laser with a minimum step size of 91 pm determined by the intra-cavity etalon ensuring longitudinal single-mode operation. The maximum step size achieved with the current driving electronics amounts to 0.6 nm at 500 Hz switching frequency. This setup shows high spatial and temporal laser beam stabilities.

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1 Introduction

The laser beam can be used as a non-contact probe for metrology in general and as an indispensable tool in combustion diagnostics. With tunable, narrow-bandwidth excitation of molecules in flames or gas streams it is possible to investigate concentration and temperature fields in a selective, sensitive and effective way [1]. Looking for compact and efficient short pulse lasers providing high repetition rates, diode-pumped all-solid-state lasers like the disk laser [2] have become an attractive alternative to commonly used excimer or dye lasers [3]. Superradiant excimer and dye lasers with an oscillating diffraction grating as an end mirror of the cavity offer wavelength switching ($\Delta\lambda > 100$ pm) from pulse to pulse [4]. This allows us to excite selected rovibronic molecular transitions of species relevant for combustion diagnostics like e.g. OH radicals. The recorded laser induced fluorescence (LIF) intensities originating from different rotational states enable one to calculate local gas phase temperatures using Boltzmann statistics. LIF can be registered simultaneously with spectral and spatial resolution by means of gated and intensified cameras supplied with appropriate optical filters.

Compared to excimer and pulsed dye lasers solid-state lasers provide low optical gain factors. The output coupler of a widely tunable disk laser typically shows a transmittance of 1…5 percent [5]. Therefore, tuning and fast wavelength switching cannot be achieved by using a diffraction grating with its considerable cavity losses. Consequently we investigated different methods for fast wavelength switching of a solid-state laser, particularly a disk laser oscillator, using optical components with only minor losses. In our disk laser system the oscillator beam (cw mode) passes through a Pockels cell for pulse generation and subsequently a regenerative amplifier operating at 1 kHz repetition rate [3]. Therefore, the wavelength changes must occur on a sub-ms time scale.

Different switching concepts were tested in the past [6, 7]. A very promising approach uses an intra-cavity Pockels cell. In the present work we explore a laser design in which two functions, i.e. narrow bandwidth operation and fast wavelength switching, are incorporated into the Lyot filter. The filter is tuned by applying an external voltage and thus varying the electro-optical activity of the filter crystal. Switching the external voltage on and off allows to quickly switch the laser wavelength between two preselected values.

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2 Experimental setup and operation

The disk laser oscillator is composed of a 200 µm thin Yb:YAG disk and an output coupler ($R = 0.98$) with a total resonator length of 320 mm. The disk has a highly reflecting coating on its rear side which is attached to the cooling unit and an antireflection coating on its front side. It is mounted in the laser head which houses the pumping optics for multiple passes of the 940 nm pump radiation from fiber-coupled InGaAs high power laser diodes. To ensure single-mode operation, frequency selective elements are inserted into the resonator: with a 4 mm thick fused silica etalon to select a single longitudinal mode and a two-stage Lyot filter (2 and 8 mm thick quartz crystals) for spectral narrowing, the laser is tunable from 1020 to 1055 nm in 91 pm steps [5]. The step size or free spectral range (FSR) is determined by the thickness of the etalon. Mounting the birefringent filter(s) under Brewster's angle ensures a highly polarized output beam. The wavelength is measured by a high resolution spectrometer (Exitec) taking advantage of high orders of refraction surveying a wavelength range of several nanometers and a wavemeter (WA-1100 Burleigh, Michelson interferometer, spectral resolution 0.28 GHz) for absolute wavelength calibration.

To achieve wavelength switching, the 2 mm quartz crystal is substituted by a 2 mm lithium niobate crystal. The crystal is gold coated on two opposing surfaces to ensure good contact to the high voltage source (PCD3H, Bergmann Messgeraete Entwicklung). Because of the different refractive indices of quartz and lithium niobate the two Lyot filters are mounted in different angles (Fig. 1). Applying a high voltage to the lithium niobate crystal filter changes its electro-optical activity. This leads to a modified transmittance curve of the filter and consequently to a wavelength change of the emitted laser beam. Alternating the high voltage results in wavelength switching between two preselected values.

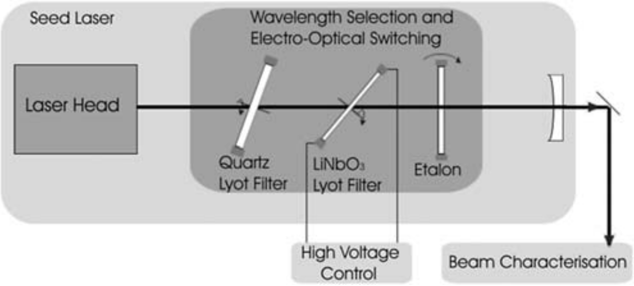

Fig. 1 Scheme of the disk laser with spectral narrowing and electro-optical wavelength switching

3 Results and discussion

The results comprise optical model calculations and experimental findings with the tunable disk laser described above.

To evaluate the tuning performance of the Lyot filter in our disk laser setup its transmittance was calculated as a function of wavelength and applied voltage following the Jones formalism [8, 9]. The eigenvalues of the related Jones matrix were evaluated, representing the transmittance. Considering a full resonator path, the total matrix M is composed of the Jones matrices of each single element in the passive resonator without active medium,

$$M = L \cdot ET \cdot OM \cdot ET \cdot L \cdot EM$$

with the electro-optically tunable Lyot filter L, the etalon ET, the end mirror EM and the output mirror OM. Lithium niobate offers a high r_{33} electro-optical coefficient (Table 1) and the results for a 2 mm lithium niobate Lyot filter are shown in Fig. 2. Varying the applied voltage changes the transmittance characteristics of the Lyot filter. Applying a voltage of several kV, a wavelength shift of several free spectral ranges (FSR) can be obtained.

The ordinary and the extraordinary refractive indices of lithium niobate are, however, different. Transmittance calculations show that a two-stage lithium niobate Lyot filter (constructed in the same way as the quartz filter) offers an overall tuning range of 3 nm only, while the quartz Lyot filter features a broad tuning range of 60 nm (Fig. 3). For the purpose of clarity in Fig. 3b only the transmittance curve of a 2 mm thick lithium niobate crystal is shown. The tuning range of a 8 mm lithium niobate filter would be even smaller by a factor of four. Broad tuning ranges comparable to that of the quartz filter could be reached in theory by use of very thin lithium niobate crystals. However, such thin crystals ($d < 0.1$ mm) cannot be manufactured with optical quality. Experimentally, a 2 mm lithium niobate crystal

Table 1 Properties of lithium niobate at 1064 nm (supplier data)

Electro-optical coefficients	
r_{31}	$3.4\ \text{pmV}^{-1}$
r_{22}	$5.6\ \text{pmV}^{-1}$
r_{33}	$30.8\ \text{pmV}^{-1}$
Thermo-optical coefficients	
dn_o/dT	$0.15 \times 10^5\ \text{K}^{-1}$
dn_e/dT	$3.85 \times 10^5\ \text{K}^{-1}$
Refractive indices	
n_o	2.322
n_e	2.156

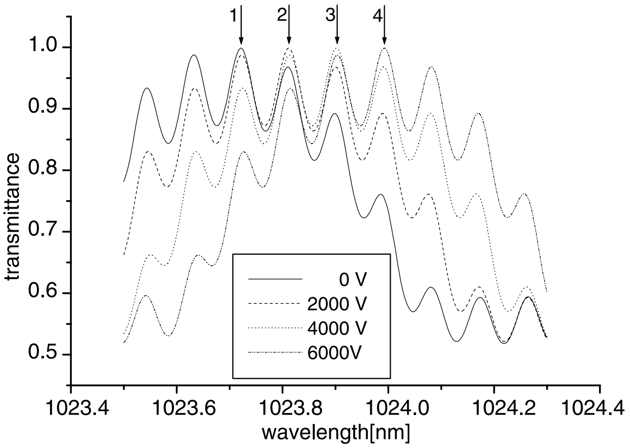

Fig. 2 Calculated transmittance of a 2 mm lithium niobate Lyot filter combined with an etalon as a function of wavelength for different tuning voltages. The *arrows* indicate the maximum transmittance for a voltage of 0 V (*arrow 1*), 2000 V (*arrow 2*), 4000 V (*arrow 3*) and 6000 V (*arrow 4*)

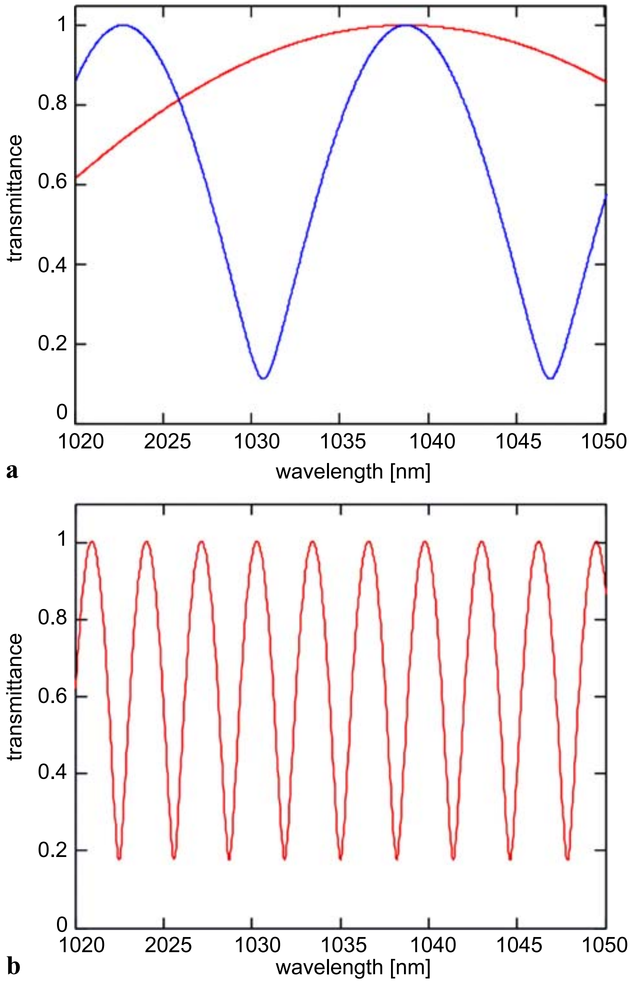

Fig. 3 Calculated transmittance curves for (**a**) each of the two plates in a two-stage (2 mm and 8 mm) quartz Lyot filter and (**b**) a 2 mm thick lithium niobate crystal

is paired with a 8 mm quartz crystal for convenient handling and a tuning range comparable to that of the two-stage quartz Lyot filter. A fast controllable power supply provides wavelength switching at high frequency.

The experimental results of disk laser emission and wavelength switching are shown in Figs. 4 and 5. In agreement with the model calculation, wavelength switching could be obtained over a range of several FSRs by applying a voltage of several kV at 500 Hz. The minimum wavelength step requires 1500 V. The emitted laser wavelength switches from the original wavelength of 1028.22 nm to the new wavelength of 1028.31 nm, corresponding to one FSR. At 2000 V and 3000 V steps of 2 and 3 FSRs are obtained, respectively (Fig. 4).

The wavelength step over 4 FSRs occurs at 4200 V. During operation above 4 kV, however, the original basic wavelength of 1028.22 nm shifts to 1028.12 nm and wavelength switching occurs between 1028.12 nm and 1028.49 nm. Wavelength switching at 5500 V and 6700 V starts from the new basic wavelength 1028.12 nm.

Several minutes after turning off the high voltage the laser switches back to its original basic wavelength of 1028.22 nm. This long time constant hints to a thermal effect induced by the applied high voltage. This shift of the basic wavelength can be compensated for by tuning the Lyot filter manually.

When switching over wide wavelength ranges of 3 or 4 FSRs the output power of the basic wavelength differs from that of the switched wavelength. This reflects the fact that the quartz Lyot filter is tuned for maximum transmission of the basic wavelength and the switched wavelength is no longer close to its transmittance maximum. Tuning the transmittance maximum of the quartz Lyot filter between the original and switched wavelengths provides a useful compromise. This, however, yields less total output power, i.e. the sum of the equal output powers at both wavelengths.

It is worth while to briefly discuss the selection of the Lyot filter material: The electro-optic activity depends on the externally applied voltage. This effect was used, for example, in special dual-wavelength lasers and allowed for extra-cavity difference frequency mixing to generate THz radiation [10]. Looking at the low electro-optical coefficients of quartz crystals ($r_{111} = r_{122} = -r_{221} = 0.48\ \mathrm{pmV}^{-1}$; $r_{123} = -r_{0,23} = 0.23\ \mathrm{pmV}^{-1}$ [11]) it was replaced by the more suited lithium niobate (Table 1). An ideal material does not only provide high electro-optical coefficients but is easy to handle, chemically stable and has optical properties, especially birefringence, similar to those of quartz. Since the crystal surfaces must stay transmissive, the electrodes can only be attached onto the non-irradiated sides of the crystal. Therefore only specific coefficients of the electro-optical tensor can be used, particularly the r_{33} coefficient. A different material may be found for the Lyot filter, having similar

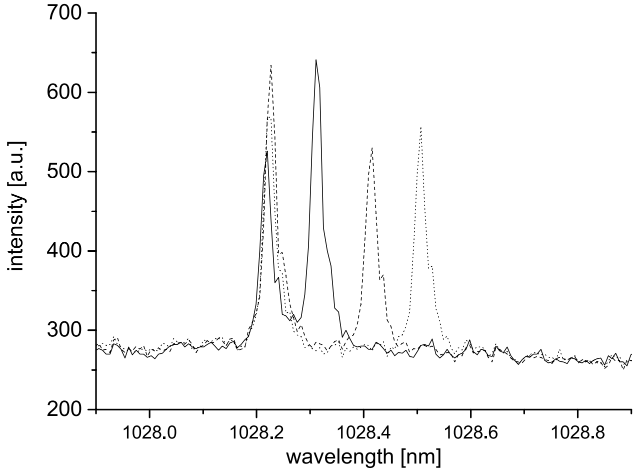

Fig. 4 Wavelength switching with the electrically tunable Lyot filter at 500 Hz and voltages below 4000 V. *Solid line*: switching 1 FSR with 1500 V; *dashed line*: 2 FSRs with 2000 V; *dotted line*: 3 FSRs with 3000 V

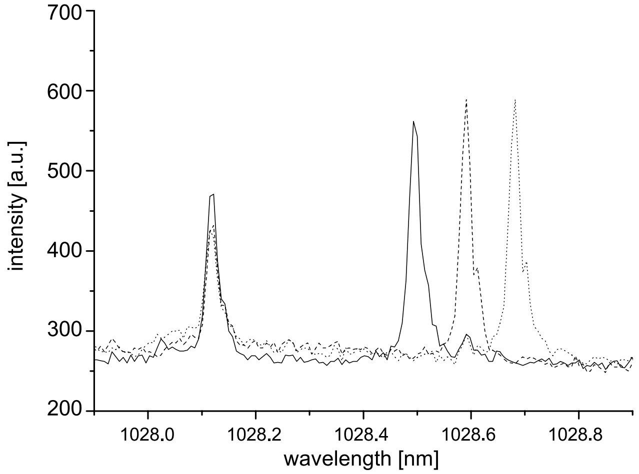

Fig. 5 Wavelength switching with the electrically tunable Lyot filter at 500 Hz and voltages above 4000 V. *Solid line*: switching 4 FSR with 4200 V; *dashed line*: 5 FSRs with 5500 V; *dotted line*: 6 FSRs with 6700 V

electro-optical properties as lithium niobate to ensure fast wavelength switching. Furthermore the difference between the ordinary and the extraordinary refractive indices must be comparable to that of quartz to maintain wavelength tuning over a broad spectral range. Additionally, the ideal material also would allow to manufacture both Lyot filters from the same material, which would result in a very convenient and compact setup of the laser.

4 Conclusion

A new device for fast electrical wavelength switching of an Yb:YAG disk laser system was designed, built up and successfully tested. Wavelength switching in discrete steps of 91 pm or multiples thereof over a wavelength range of more than 600 pm with a switching frequency of 500 Hz was demonstrated.

The step size of wavelength switching may be adjusted to specific requirements by selecting an etalon of proper thickness. The beam polarization is not changed during wavelength switching. The temporal and spatial beam stabilities are excellent. At higher voltages the Lyot filter needs to be tuned slightly to compensate for thermal effects in lithium niobate. Switching over a step size exceeding 100 pm can lead to an asymmetry in the output power at the two wavelengths due to the wavelength dependence in the transmittance curve of the quartz niobate filter.

Summarizing, our results prove that the electrically tuneable Lyot filter provides a very promising setup for efficient and convenient wavelength switching of a solid-state laser on a ms time scale.

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References

1. K. Kohse-Hoeinghaus, *Applied Combustion Diagnostics* (Taylor & Francis, New York, 2002)
2. A. Giesen, H. Huegel, A. Voss, K. Wittig, U. Brauch, H. Opower, Appl. Phys B **58**, 365 (1994)
3. W. Paa, D. Mueller, H. Stafast, W. Triebel, Appl. Phys. B **86**, 1 (2007)
4. D. Grebner, W. Triebel, D. Mueller, Rev. Sci. Instrum. **8**, 2965 (1997)
5. A. Baum, D. Grebner, W. Paa, W. Triebel, M. Larionov, A. Giesen, Appl. Phys. B **81**, 1091 (2005)
6. M. Schnepp, Diploma thesis, University of Applied Sciences, Jena (2004)
7. M. Franke, W. Paa, W. Triebel, M. Schnepp, H. Stafast, Appl. Phys. B **94**, 65 (2008)
8. D.R. Preuss, J.L. Gole, Appl. Opt. **19**, 702 (1980)
9. N. Hodgson, H. Weber, *Laser Resonators and Beam Propagation* (Springer, New York, 2004)
10. M. Brunel, N.D. Lai, M. Vallet, A. Le Floch, F. Bretenaker, L. Morvan, D. Dolfi, J. Huignard, S. Blanc, T. Merlet, Proc. SPIE **5466**, 131 (2004)
11. S. Haussuehl, *Kristallphysik* (Physik Verlag, Verlag Chemie, Weinheim, 1983)