A new compact high brilliance diode laser type

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ABSTRACT

Our work deals with a new approach to improve the beam quality of diode lasers, which is still insufficient for many applications. We propose time-multiplexing, where several pulsed laser diode beams are guided onto a common optical path. This allows to superpose the power of the diodes while maintaining the beam parameter product of a single laser diode. Pulsed operation of continuous wave laser diodes was shown to be possible up to pulse enhancement factors of ten provided that pulse duration is <300 ns. We use a fast digital optical multiplexer built up by a cascade of binary optical switches. For the latter we use a polarisation switch (voltage-driven LiNbO3-crystal) followed by a polarisation filter, which allows addressing of two optical paths. Instead of direct on/off-switching we drive the crystals with a harmonic voltage course to avoid ringing caused by piezo-electricity. Up to now an optical power of 10.5 W was generated, 13 W are expected with some improvements. With the use of new 8W laser diodes even the generation of 25 W will be possible.

Keywords: diode laser, high brilliance, pulsed laser diodes, time-multiplexing, electro-optic modulator

1. INTRODUCTION

Due to their compactness and high efficiency diode lasers play an increasingly important role in modern industrial manufacturing. Soldering, brazing, welding of plastics, hardening, cladding and heat conduction welding are their main applications. Unfortunately the poor beam quality of diode lasers limits or prevents their use in applications like cutting of metals, marking or drilling.

The performance of a laser depends not only on its optical power but also on beam quality, which can be characterized by the so called beam-parameter-product (*BPP*). It is defined as the product of the beam-radius in the beam waist w_0 and the far-field divergence angle Θ_0 (half width at $1/e^2$) [1]: $BPP = w_0\ \Theta_0$. A small beam parameter product corresponds to a high beam quality. For the astigmatic diode laser beam an average beam parameter product <BPP> can be defined as the geometric mean of the values for the slow and the fast axis.

The main reason for the poor beam quality of diode lasers is the incoherent combination of light emitted by many beam sources. One way to improve beam quality is coherent coupling of laser diodes, which had limited success [1]. We suggest time-multiplexing, up to now only proposed for solid state lasers [2] and CO_2-lasers [3], as a new method to combine individual laser diode beams. In the described setup laser diodes are emitting laser pulses with high peak power, operated such that one diode after another emits a pulse. The pulses are directed onto a common optical path by means of a fast scanner. The resulting pulse train has the same beam quality as a laser beam produced by only one laser diode but an average beam power in the order of the peak power of one laser diode.

2. SCHEME OF TIME-MULTIPLEXING

For an effective use of time-multiplexing a very fast scanner is needed, so we use an inverse digital scanner based on electro-optics [4]. A schematic diagram of our experimental setup for multiplexing of four laser diodes is depicted in Figure 1.

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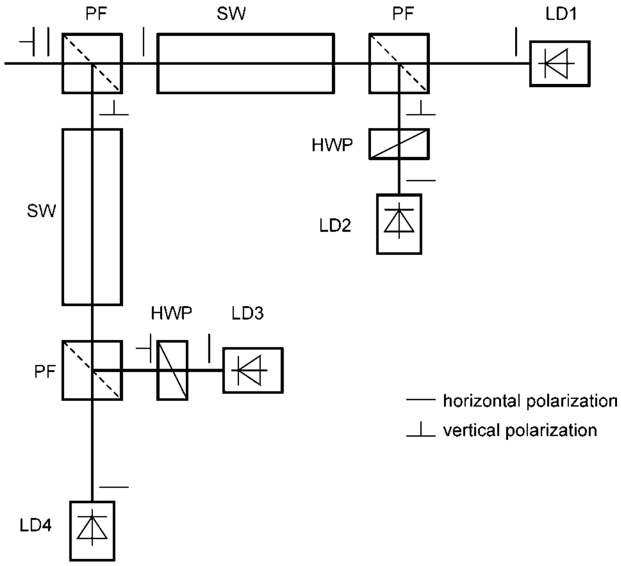

Figure 1: Time-multiplexing of four laser diodes: PF…polarisation filter; SW…polarisation switch; LD…laser diode; HWP…half-wave-plate.

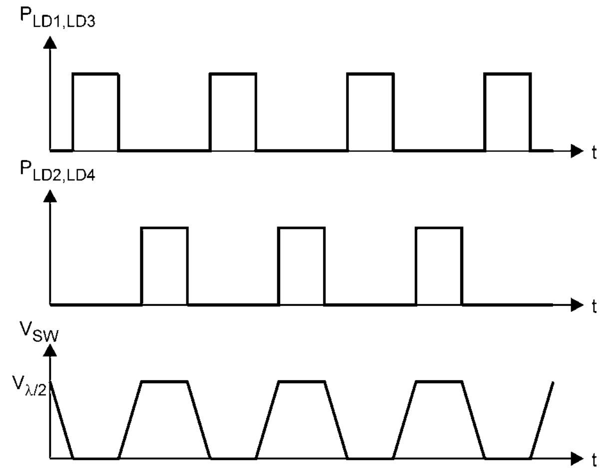

Figure 2: Switching sequence. top: optical output of laser diodes 1 and 3; middle: optical output of laser diodes 2 and 4; bottom: idealized voltage course at crystal electrodes

The multiplexer consists of a combination of two half-wave-plates, three polarisation filters and two polarisation switches (Pockel's-cells) made of $LiNbO_3$-crystals. The polarisation of linearly polarised light passing the crystal can be turned by 90° by applying the half-wave-voltage to the electrodes of the switch. Figure 2 shows the switching sequence: The voltage across the switches is turned on and off with constant frequency and equal on- and off-times. During a period without applied voltage the laser diodes 1 and 3 emit a pulse. The light from laser diode 1 is horizontally polarised and passes the filters straightforward. With the help of a half-wave-plate the polarisation of the light originating from laser diode 3 is changed so that it is reflected twice in the polarisation filters. By means of the last polarisation filter the two pulses are superposed by polarisation-multiplexing.
Laser diodes 2 and 4 emit their pulses while voltage is applied to the crystal electrodes. The crystals change the polarisation state from vertically to horizontally polarised and vice versa. This way the light from laser diode 2 passes the last filter straightforward whereas the light from laser diode 4 is reflected. This ensures that the light pulses are guided towards the same direction as the pulses of the laser diodes 1 and 3.
Note that if the pulse sequence for the diodes were exchanged the output beam would propagate perpendicular to the direction indicated in Figure 1 (towards the top of the figure), which is a simple way to address two different paths.

3. PULSED OPERATION OF LASER DIODES

One key issue of our setup is the generation of the desired optical pulses. In [5] it is shown that even ordinary continuous wave (cw) laser diodes are capable of emitting laser pulses with peak powers far above their specified power provided that the pulse length is below 300ns. For our setup we use passively cooled laser diodes from JDS Uniphase (4W, 960nm, 100x1µm aperture, C-mount). These are pulsed with a pulse repetition frequency of 1.1MHz with pulse widths of 300ns (FWHM) and a pulse enhancement factor of 3. An average optical power of 3.6W is emitted by each diode. We decided to use only 90% of the specified cw-power to maintain the life time of the diodes used in the setup. When operated with these parameters the laser diodes show the same beam quality as in cw-operation.
Up to now we realized with one laser diode more than 80 hours of pulsed operation at an average output power of 4 Watt (100% of the specified cw-power) without seeing any degradation of diode performance.
The driver topology uses capacitors, which are discharged with a fast MOS-FET via the laser diode. One drawback of pulsed operation is the additional loss, rooting in the stray impedances of the leads to the laser diode. The latter cause an enhanced driving voltage for a defined average current (when compared to cw-operation). E.g. at 4,6A average current cw-operation needs a driving voltage of 1,9V whereas pulsed operation (PRF…1,1MHz, pulse width…300ns) needs

3,7 V, which is nearly twice as much. Hence the electrical efficiency drops from ~50% at usual cw-operation to ~25% at pulsed operation. Figure 5 shows the pulse shape produced by our driver. The rising edge of the optical pulse takes 100 ns. A significant faster and more efficient switching would be possible if an inductor would be used as the energy storage. When the latter is fed with current and then rapidly switched to the laser diode the stray inductivity would be fast overcome [5].

4. POLARISATION SWITCHES

The polarisation switches are z-cut $LiNbO_3$-crystals on which a transverse electric field can be applied via electrodes on the yz-surfaces. The plane of polarisation of linearly polarised light passing the crystal along the z-axis will be turned by 90° if the so called half-wave-voltage $V_{\lambda/2}$ is applied. The theoretical value for $V_{\lambda/2}$ depends on the electro-optical coefficient r_{22}, crystal length $L = 30\,\mathrm{mm}$, crystal thickness $d = 1.8\,\mathrm{mm}$, ordinary refractive index $n_0 = 2.244$ (@960nm, stoichiometric material [6]) and on the light wavelength $\lambda = 960\,\mathrm{nm}$:

$$V_{\lambda/2} = \lambda\, d \,/\, (2\, L\, r_{22}\, n_0^3) \tag{1}$$

r_{22} depends on the frequency due to resonance effects [7]. For low frequencies $r_{22} = 6.8\,\mathrm{pm/V} \rightarrow V_{\lambda/2} = 377\,\mathrm{V}$ and for high frequencies $r_{22} = 3.4\,\mathrm{pm/V} \rightarrow V_{\lambda/2} = 754\,\mathrm{V}$. In our experiment with a frequency of 1.1MHz in the region of the first shear-wave resonance we measured $V_{\lambda/2} \sim 480\,\mathrm{V}$.
The relative intensity of the component with polarisation turned by 90° (I_{90}/I_0) depends on the applied voltage. The corresponding transfer function of the crystal with subsequent polarisation filter and linearly polarised light going in z-direction, with polarisation parallel to the filter, is (Figure 3b) [7]:

$$\frac{I_{90}}{I_0} = \cos^2\left(\frac{\pi}{2}\frac{V}{V_{\lambda/2}}\right) \tag{2}$$

This is the transfer function for the laser diodes 1 and 3, whereas for the diodes 2 and 4 there would be a sine instead of cosine.

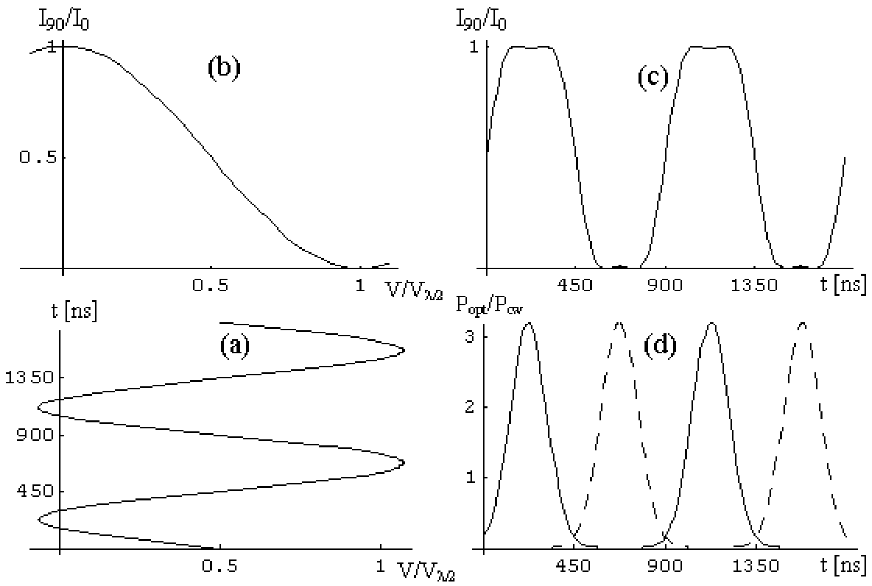

Figure 3: Driving the multiplexer with a harmonic voltage course; a) Voltage course at crystal electrodes b) transmission function of crystal between parallel polarisers c) modulation of polarisation d) laser pulses from laser diodes 1, 3 (drawn through) and 2,4 (dashed)

To achieve now the desired modulation direct on/off-switching of the half-wave-voltage at the desired high frequency is not possible, since it is energy consuming and causes ringing because of the piezoelectric properties of $LiNbO_3$. Instead we apply a harmonic voltage course to the electrodes. A DC-part of 0.5 $V_{\lambda/2}$ is superposed by an alternating voltage with an amplitude of approximately 0.55 $V_{\lambda/2}$ and a frequency of 1.1 MHz (Figure 3a). Due to the transfer characteristic of the crystal (Figure 3b) a modulation of light polarisation as depicted in Figure 3c can be achieved. This polarisation course represents a good approximation of the desired on-off-behaviour. Figure 4 shows the experimental verification of the calculated transmission.

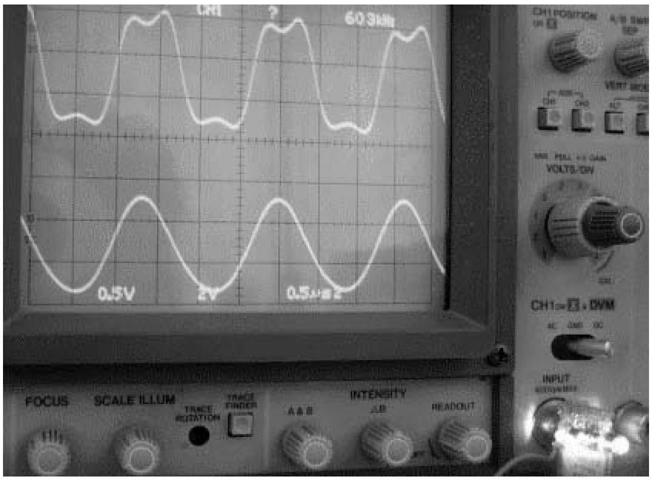

Figure 4: Transmission (upper signal) of the harmonically (lower signal) driven $LiNbO_3$-crystal with subsequent polarisation filter crossed to initial polarisation. In the lower right corner the photodiode illuminated by the laser diode can be seen.

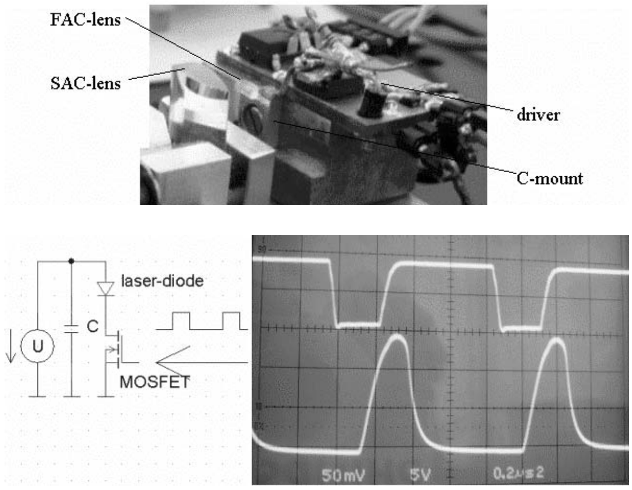

Figure 5: Laser diode driver and oscilloscope shot of pulsed operation with the control signal (upper signal) and the signal detected with the photo diode (lower signal). The control signal goes to an inverting MOSFET-driver which charges/discharges the gate of the switching MOSFET indicated in the sketch of the driver topology on the left hand side.

5. OPTICAL ADJUSTMENT

Up to now we assumed that the light propagates along the z-axis of the crystal. Figure 6 shows an experimental setup that visualizes the effect on polarisation for beam directions that deviate from the z-axis. With the diffuser removed the optical behaviour is equal to that of laser diode 1 in Figure 1.

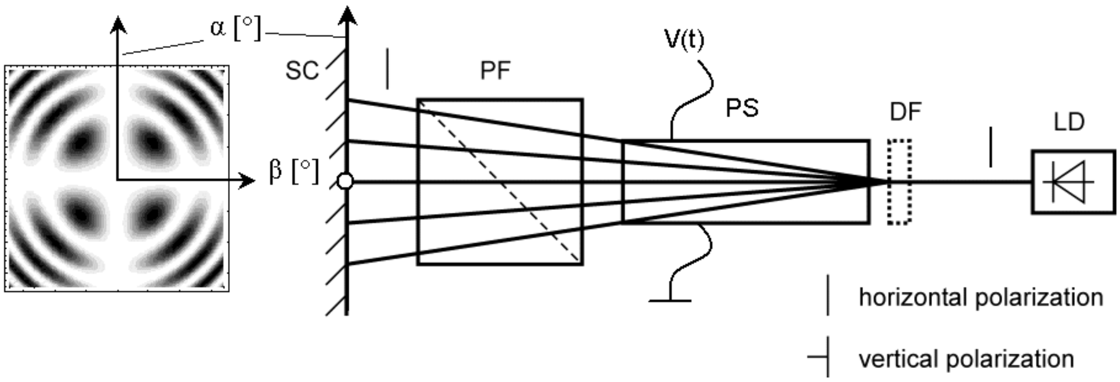

Figure 6: Setup to visualize the effect on polarisation for different directions of propagation: SC…screen; PF…polarisation filter (analyser); PS…polarisation switch; DF…diffuser; LD…laser diode; V(t)…time dependent electrode voltage; α, β…angle coordinates.

In this setup the crystal is followed by a polarisation filter (analyser) parallel to the initial polarisation. The light is diffused in front of the crystal so that it propagates through the crystal in several directions. With the help of the filter only the components with initial polarisation are transmitted to the screen. The corresponding voltage-dependent interference pattern J is calculated with [8]:

$$J(V,\alpha,\beta) = \left(\sin 2\varphi(V,\alpha,\beta)\cos\left\{\pi L\left[n_1(V,\alpha,\beta) - n_2(V,\alpha,\beta)\right]/\lambda\right\}\right)^2 \tag{3}$$

α, β are the angles between the optical ray and the z-axis in x- and y-direction. $\varphi(V, \alpha, \beta)$ is the angle between the analyser and the main axis of the cross-section (an ellipse) of the voltage dependent index-ellipsoid with the plane normal to the desired direction (α, β). The refractive indices n_1 and n_2 are the lengths of the main axes of this cross-section. φ, n_1, n_2 are calculated by determining the eigenvalues and eigenvectors of the corresponding reduced index matrix. Note that for our configuration with the electric field parallel to x-axis setting $\alpha=\beta=0$ yields $\varphi=45°$ and $n_1 - n_2 = V n_o^3 r_{22}/d$ which leads exactly to equation (2).

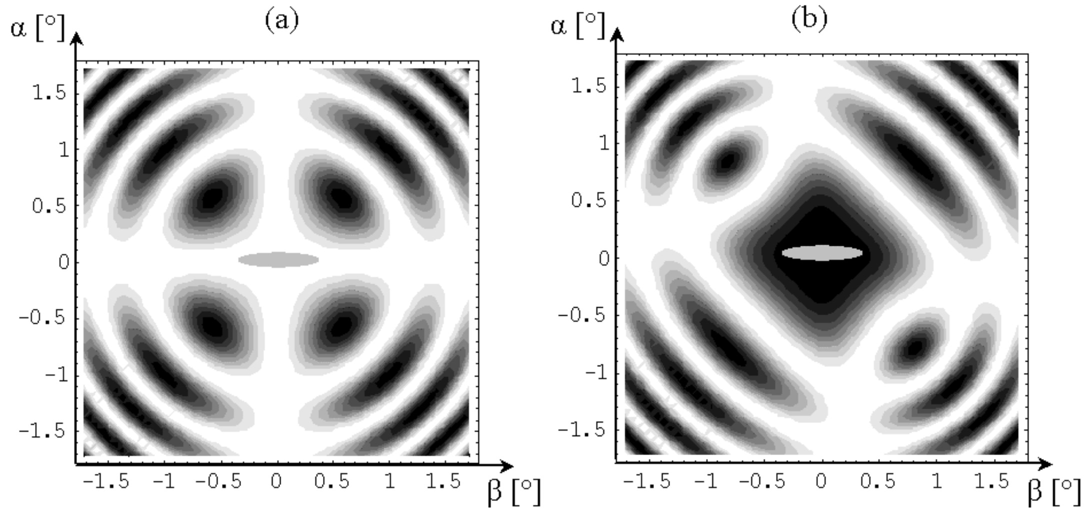

Figure 7: Patterns generated by the setup of Figure 5; a) Without voltage b) With applied half-wave-voltage; The grey ellipse shows the far field intensity of the collimated laser diode beam when the diffuser is removed.

Figure 7 shows the respective pattern when no voltage is applied to the electrodes of the crystal (Figure 7a) as well as when the half-wave-voltage is applied (Figure 7b). In this illustration white areas represent directions where no change of polarisation occurs. Figure 7a represents the pattern needed for the laser 1 and 3, while the pattern of Figure 7b is the one for the diodes 2,4.

Obviously the divergence of the beam has to stay within a limited range. We consider Figure 7b: The maximum divergence β_{max} for a light ray diverging from the optical axis in the yz-plane (slow axis direction) with a corresponding relative energy loss $q=J(V_{\lambda/2}, 0, \beta_{max})$ can be deviated from equation (3) as follows (n_o, n_e…ordinary and extraordinary refractive index):

$$\beta_{max} = \sqrt{\frac{\lambda}{L}\frac{\arccos\sqrt{2q}}{\pi(1-n_e^2/n_o^2)}} \cong \sqrt{\frac{\lambda}{L}\frac{\arccos\sqrt{2q}}{2\pi}\frac{n_o}{n_o-n_e}} \tag{4}$$

This yields $\beta_{max} = 6{,}7\,\text{mrad}$ (=0,38°) for $q = 5\%$ (n_o=2.244, n_e=2.1605 @ λ=960 nm [7]). The laser diodes have a slow axis aperture of d_{SA}=100µm and a f = 10 mm cylindrical lens is used for slow axis collimation, which yields with the estimation $d_{SA}/(2f)$ = 5mrad (=0,29°) a sufficient small far field divergence. The fast axis divergence after the FAC-lens is only ~1 mrad (=0,06°). Fig. 8 illustrates these results.

One simple mean to achieve a larger acceptance angle is the reduction of crystal length as equation (4) shows. This of course would result in higher driving voltages. An alternative is the use of crystals with lower birefringence since the acceptance angle is proportional to the inverse of the square root of the difference between the ordinary and extraordinary refractive index, as seen in the right hand side of equation (4). This question is important for laser sources like diode laser bars offering a much lower beam quality in the slow axis direction.

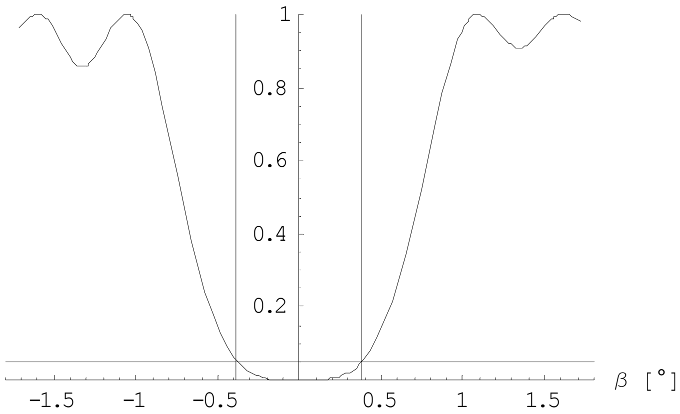

Figure 8: Transmission along horizontal axis (*β*-coordinate) in Figure 7b for a 30mm stoichiometric z-cut LiNbO3-crystal with half wave voltage applied on yz-electrodes for 960nm. Vertical lines: Formula (4) for the maximum admissible beam divergence yields 6.7mrad (= 0.38°) for $q = 0.05$ (horizontal line).

6. SWITCHING EFFICIENCY

Consider laser diode 1 (or 3) in Figure 1 with the corresponding crystal and polarisation filters. The percentage of power passing the last polarisation filter in the desired direction can be calculated as[1]

$$E_{90} / E_0 = \iiint_{t,\alpha,\beta} J\left[V(t),\alpha,\beta\right] I(t,\alpha,\beta)\, dt\, d\alpha\, d\beta \Big/ \iiint_{t,\alpha,\beta} I(t,\alpha,\beta)\, dt\, d\alpha\, d\beta \quad , \tag{5}$$

where E_0 is the initial pulse energy, E_{90} is the pulse energy after the analyser, $I(t, \alpha, \beta)$ is the time- and direction dependent intensity of the laser pulse, and $V(t)$ is the electrode voltage course (Fig. 3a). For laser pulses of Gaussian shape in time- and angle-coordinates (300 ns pulse duration, 10 mrad slow axis divergence, 2mrad fast axis divergence, all FWHM) centred on the minima (maxima) of the voltage course shown in Fig. 3 we calculated an overall transmission of 95%. For the laser diode 2 (or 4) whose light enters the crystal vertically polarised and with a temporal phase shift of half the oscillation period (Fig. 3d), J (equ. (3)) must be replaced by $1-J$, which yields again 95% of light taking the desired path.

7. EXPERIMENTAL RESULTS

The experimental setup (Fig. 9) generates a laser beam with an optical power of 10.5W in the desired direction after the last polarisation filter. In the perpendicular undesired direction we measured 1.9W of optical power, hence the loss due to insufficient polarisation is 1.9/(10.5+1.9) = 15%, which is high compared to the predicted 5% loss of equation (5). We suppose that mechanical oscillations of the piezo-electric crystals influence polarisation-turning via the elasto-optic coefficients in an undesired way.

The overall optical power of the four laser diodes is 4 x 3,6 = 14.4 W. Unfortunately we have rather high losses due to back reflections and due to insufficient polarization of some laser diodes. For the latter we measured polarization rates lying between 90% and 98%. Due to these losses only 12,4 W reaches the last polariser.

We expect that an overall efficiency of 90% and generation of almost 13 W optical power with an average beam parameter product of 1,7mmmrad can be achieved with an improved and much more compact setup. With new laser

[1] The spectral width of our laser diodes is about 8nm, which is for this application so small that we can neglect its influence, hence no integration over the wavelength appears in equation (5).

diodes already at the market with 8 W specified cw-power (100 µm-aperture width, 960 nm, JDS Uniphase) a power of 25W will be possible by time-multiplexing of four laser diodes.
The average beam parameter product (BPP) is calculated by the emission values of one laser diode. For the slow axis holds: $BPP_{SA} = 4{,}8$mmmrad (corresponding to 100 µm aperture width and 11° FWHM beam divergence). It is known [1] that a state of the art FA-collimation increases the BPP in the fast axis by a factor of two, hence we calculate for the fast axis $BPP_{FA} = 2\lambda/\pi = 0{,}61$ mmmrad (diffraction limited output). The theoretical average beam parameter product $BPP = BPP_{SA}^{1/2}\ BPP_{FA}^{1/2} = 1{,}7$ mmmrad, which presumes an adjustment of the diode laser beams according to state of the art.
Fig. 10 shows a new miniaturized setup with an optical arrangement equal to the one of Fig. 9 but with a new design of electronics, allowing an extremely compact laser head with lateral dimensions of 115 x 115 mm. The achieved parameters are similar to the old setup, but complete testing is not completed up to now.

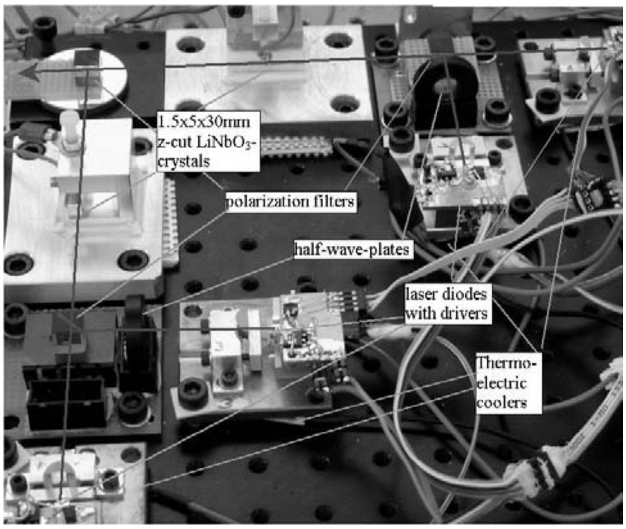

Figure 9: The laboratory setup for time-multiplexing of four laser diodes.

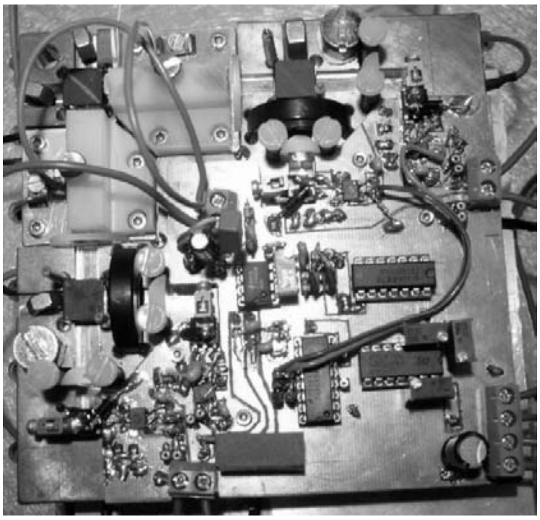

Figure 10: A compact prototype (dimensions 115 x 115 mm) for time–multiplexing of four laser diodes

8. COMPARISON OF PARAMETERS

Fig. 11 shows a comparison of the boundaries of several types of lasers (diode-, CO_2- and diode pumped solid state lasers) in respect to laser power and beam parameter product, as well as the demands of typical manufacturing processes regarding these parameters. The properties of the beam generated by our setup and the expected results for similar setups with 8 and 16 laser diodes are also indicated showing that the limits for diode lasers are noticeably exceeded with the help of time-multiplexing. This could open up the important application of marking, which up to now can only be accessed by solid state lasers.
It should be mentioned that the concept of time-multiplexing can easily be combined with additional multiplexing techniques like wavelength- or position-multiplexing. A long-term objective is to open up cutting of metals to diode lasers by combining different multiplexing techniques. We expect that in the meantime applications already accessible to diode lasers could profit from time-multiplexing.
One further possibility lies in time-multiplexing of pulsed diode laser bars. These are used not only for pumping of solid state lasers but also for direct medical applications. However other optical materials would be needed since the acceptance angle of $LiNbO_3$ is too small for diode bars as discussed earlier.

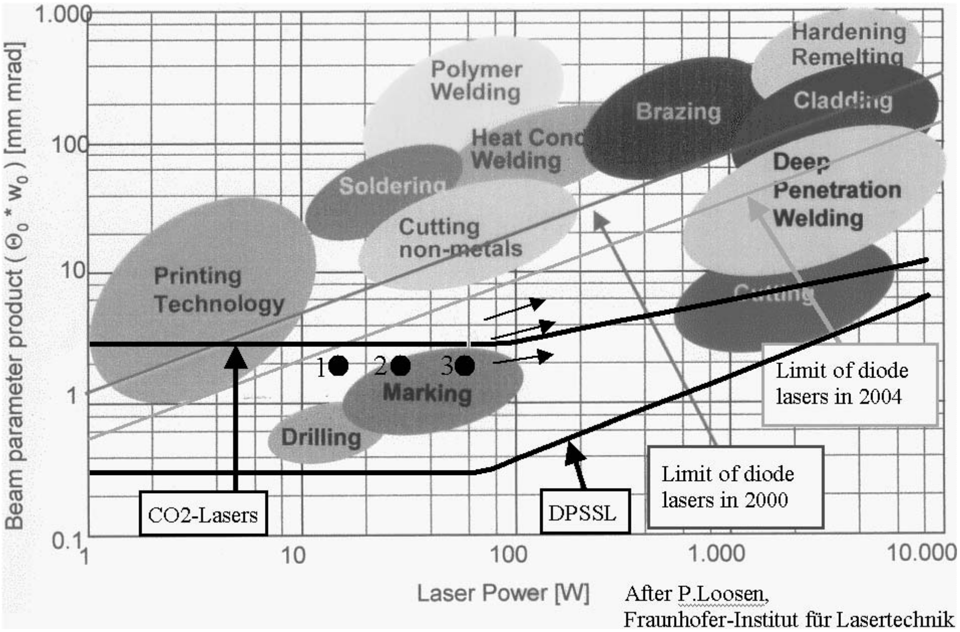

Figure 11: Parameters of laser material processing and limits of different lasers. The black numbered spots indicate time-multiplexing of 4 (1), 8 (2) and 16 (3) diodes.

9. CONCLUSION

The concept of time-multiplexing as a method to increase the beam quality of diode lasers is introduced. A fast electro-optical digital multiplexer able to combine the beams of four laser diodes working in pulsed operation was realized first as a laboratory setup then as a miniaturized prototype for a diode laser head. It utilizes a combination of polarisation filters and Pockel's-cells made of lithium niobate. Theoretical and experimental results show that applying a harmonic voltage course to the electrodes of the crystal is an effective way to achieve fast polarisation switching while avoiding ringing. Our setup generates a laser beam with an optical power of 10,5 W and a theoretical average beam parameter product of 1,7 mmmrad.

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