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Tunable single frequency microchip Nd:YAP MOPA laser operating at 1.08 µm

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Abstract
A longitudinally laser diode (LD)-pumped Nd:YAP microchip master oscillator power amplifier (MOPA) system operating at 1.08 µm was demonstrated. The system consisted of a longitudinally LD-pumped monolithic Nd:YAP microchip master laser and a two-stage disc amplifier. The cavity length of the master oscillator was 500 µm. The short cavity length lead to a large frequency separation between the resonator modes and hence single longitudinal mode operation was achieved. Pumped by a high-brightness LD an output power of 155 mW in both single longitudinal and transverse mode was generated. To scale to a high power, the output power from the master oscillator was amplified by amplifier discs. The amplified output power was 1.43 W. The central wavelength of the laser system was tuned by changing the cavity length and refractive index via temperature. Using a shorter master oscillator (L = 310 µm) a continuous output wavelength tuning over the gain profile of 0.9 nm was realized. To our knowledge this is the first study of a MOPA system based on an LD-pumped microchip Nd:YAP laser.

(Some figures may appear in colour only in the online journal)

1. Introduction
Generation of both single axial and single transversal mode laser radiation (SM) with high average output is necessary for various applications in industry and science. Examples are the measurement of atomic/molecular absorption spectra, the determination of small-scale shifts using Michelson interferometers (e.g. gravitational wave detector), and laser radar. Narrow linewidth lasers are also of interest for the development of length and wavelength standards. A single transverse mode, so-called TEM₀₀ mode operation, is somewhat easy to achieve by controlling the laser beam diameter, e.g. with a suitable aperture inside the laser resonator. Hence, in recent decades much effort has been made on developing the techniques to realize single longitudinal mode operation of solid state lasers. Many techniques were successfully applied to solid state lasers, such as twisted mode resonators [1, 2], frequency selection with intracavity elements, such as etalons or birefringent filters [3], coupled resonators [4] and unidirectional ring resonators [5]. Compared to these methods, monolithic microchip solid state lasers represent a simple and effective way to realize SM laser operation, especially for laser materials with a high rare-earth ion doping concentration.

Microchip lasers consist of a monolithic plane parallel polished microcrystal with dielectric cavity mirrors deposited directly on the surfaces [6–8]. These lasers have presented good efficiency in single frequency operation in various ion–host combinations [9–12]. Both actively and passively Q-switched operation has been obtained with pulse lengths in the nano- and picosecond range [10].

In monolithic microchip lasers, single-frequency operation is guaranteed by short cavity lengths, since the
index $d$

coefficient $\alpha$
to tune the laser wavelength by temperature variation. The condition is very useful for high-power SM operation.

amplified in the same gain area and below the threshold. This value. The two neighbour modes are suppressed since they are is satisfied. In this case the mode in the centre of the gain bandwidth ($\Delta \nu$) over the whole gain bandwidth then only one mode could have enough gain and start to oscillate. This condition is important for a tunable microchip laser which is designed to operate in SM over a maximum range. But it is worth noticing that still only one mode occurs if one mode is shifted to the centre of the gain bandwidth, e.g. by temperature tuning and the condition of $\Delta \nu \geq 1/2 \Delta \nu_0$ is satisfied. In this case the mode in the centre of the gain profile will oscillate first and saturate the gain to its threshold value. The two neighbour modes are suppressed since they are amplified in the same gain area and below the threshold. This condition is very useful for high-power SM operation.

A natural benefit of the short cavity is the possibility to tune the laser wavelength by temperature variation. The change in wavelength depends on both the thermal expansion coefficient $\alpha_n$ and the temperature variation of the refractive index $dn/dT$ of the laser material [14]. The resonant frequency of the laser cavity changes with cavity length according to

$$\frac{dv}{v} = -\frac{dl}{l_R}, \quad (2)$$

where $v$ is the lasing frequency and $l_R = nL$ is the resonator optical length. A change of temperature leads to a thermal expansion of the resonator and a thermal-stress-induced change of the refractive index. To the first order, stress-related index changes can be neglected. Therefore, thermally induced length and refractive index changes can be expressed by

$$\frac{dl}{dT} = nL \left( \alpha_e + \frac{1}{n} \frac{dn}{dT} \right). \quad (3)$$

Inserting equation (2) into (3) yields

$$\frac{dv}{dT} = -v \left( \alpha_e + \frac{1}{n} \frac{dn}{dT} \right). \quad (4)$$

Using the specifications of Nd:YAP listed in table 1, the $dv/dT$ was calculated to be $-3.3$ GHz K$^{-1}$.

### 2. Nd:YAP as laser material

Nd:YAP, also known as Nd:YALO, with Nd$^{3+}$ located in the crystalline host, yttrium–aluminum–perovskite, is a laser material which was investigated intensively in the 1970s and the early 1980s. There was the hope that some disadvantages of the commonly used Nd:YAG could be overcome by this material. The cubic crystal structure of Nd:YAG causes problems if polarized laser operation is desired. High losses amounting up to 25% were observed in strongly pumped, polarized Nd:YAG lasers. It is caused by thermally induced birefringence. When a polarized laser beam transmits through the laser crystal with spatially varied birefringence induced by strong pump, it is depolarized and spatially structured. The depolarization and bifocusing result in losses and, consequently, decrease the efficiency. Therefore, birefringence compensation is mandatory for polarized high-power Nd:YAG lasers. Although the thermally induced birefringence can be compensated by certain techniques [17–20], it will make the laser system complicated and unstable.

Unlike cubic YAG, the Perovskite structure of YAP is orthorhombic and consequently yields polarized laser output.

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**Table 1.** Main optical properties of Nd:YAP and Nd:YAG at the laser lines $\lambda_1 = 1080$ nm and $\lambda_1 = 1064$ nm respectively [15, 16].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Nd:YAG ($Y_3Al_5O_{12}$)</th>
<th>Nd:YAG ($YAlO_3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd$^{3+}$ segregation ($K_{nl}$)</td>
<td></td>
<td>0.18</td>
<td>0.8–0.9</td>
</tr>
<tr>
<td>Max. Nd$^{3+}$ concentration</td>
<td></td>
<td>1.25 at.% Nd$^{3+}$</td>
<td>1.8 at.% Nd$^{3+}$</td>
</tr>
<tr>
<td>Refractive index ($n$)</td>
<td></td>
<td>1.82 @ 1.06 $\mu$m</td>
<td>1.94 @ 1.08 $\mu$m</td>
</tr>
<tr>
<td>Linear dispersion ($dn/dT$)</td>
<td>$10^{-6}$ K</td>
<td>9.9</td>
<td>9.7</td>
</tr>
<tr>
<td>Thermal expansion coefficient ($\alpha_n$)</td>
<td>$10^{-6}$ K</td>
<td>4.3</td>
<td>8.2</td>
</tr>
<tr>
<td>Absorption coefficient ($\alpha_0 @ \lambda_p$)</td>
<td>cm$^{-1}$</td>
<td>9 @ 808 nm</td>
<td>11.5 @ 813 nm</td>
</tr>
<tr>
<td>FWHM of pump line ($\Delta \lambda_{p}$)</td>
<td>nm</td>
<td>0.9 @ 1.1 at.% Nd$^{3+}$</td>
<td>1.1 @ 1.1 at.% Nd$^{3+}$</td>
</tr>
<tr>
<td>FWHM of laser line ($\Delta \lambda_{l}$)</td>
<td>nm</td>
<td>0.6 @ 1.1 at.% Nd$^{3+}$</td>
<td>0.9 @ 1.1 at.% Nd$^{3+}$</td>
</tr>
<tr>
<td>$\Delta \nu_0$</td>
<td>GHz</td>
<td>160</td>
<td>225</td>
</tr>
<tr>
<td>Fluorescence life time ($\tau_f$)</td>
<td>$\mu$s</td>
<td>220</td>
<td>180</td>
</tr>
<tr>
<td>Emission cross section ($\sigma_e$)</td>
<td>cm$^2$</td>
<td>$2.7 \times 10^{-19}$</td>
<td>$2.4 \times 10^{-19}$</td>
</tr>
</tbody>
</table>

---

**Figure 1.** Spectrum of longitudinal modes within a gain material. Modes above threshold are amplified during optical pumping.
Investigations of high-power YAP lasers in both the pulsed and cw regime showed comparable thresholds and efficiencies to YAG [21–24]. The main optical properties of Nd:YAG and Nd:YAP are summarized in table 1. The possibility of high Nd concentration and a broad line width of both pump and laser line suggest that Nd:YAP is a promising material for tunable LD-pumped microchip lasers. In 1980s the difficulties with purity growth of the YAP crystal prevented its wide usage [25]. But presently YAP laser crystals can be grown in high optical quality by several manufacturers. This renews interest in YAP crystal applications [26–28].

3. Experimental results

The laser system as in figure 2 was built up. It was a MOPA system. The MOPA concept is always very useful to scale the maximum SM output power that is restricted by a single-crystal oscillator. The essential temporal and spatial coherence and maximal achievable beam quality were determined by the master oscillator, whereas the output power was scaled in amplifier stages. To reach a high brilliance of the complete system, the beam quality should not be degraded while passing through the amplifiers.

3.1. Master microchip oscillator

The master laser used in our MOPA system is a LD-pumped Nd:YAP microchip laser. A microchip with a doping concentration of 0.8 at.% Nd, diameter of 8 mm and a thickness of 500 µm was used. The monolithic laser resonator was formed by the plane parallel polished crystal surfaces. The input surface was coated for high reflectivity at 1.08 µm and high transmission around 813 nm. The output surface had a high reflective coating for 813 nm and a reflectivity of 99.6% at 1.08 µm. This design ensured an efficient laser operation at 1.08 µm and high transmission around 813 nm. The output surface had a high reflective coating for 813 nm and a reflectivity of 99.6% at 1.08 µm. This design ensured an efficient laser operation at 1.08 µm. The microchip was held from the front and back sides by a copper heat sink and the temperature was controlled by a TEC cooler system. A pump source (Spectra Diode Labs SDL-2362) delivering 1 W output power at 813 nm was used to pump the microchip laser longitudinally. A lens system consisting of a collimator lens (f = 4 mm), a cylindrical lens (f = 63 mm) for fast-axis collimation and an 11 mm focal length lens was used to couple the pump light into the Nd:YAP microchip. This coupling lens system was designed to guarantee a good overlap of the pump beam and laser TEM_{00} mode volume.

The maximum output power of the microchip master laser was 155 mW with a M²-number of 1.2. They were measured by a power detector ‘PS-310 WB’ from ‘Gentec Inc.’ and a beam propagation analyser ‘SpiriconM²-200’. The output power versus the pump power is shown in figure 3. The laser threshold is 76 mW and the optical slope efficiency is 27%. The laser was operated at a temperature of 39 °C to guarantee SM operation. Since the longitudinal mode spacing was designed to be smaller than half of the gain bandwidth (Δν > Δν₀/2) it is necessary to shift the mode into the centre of the gain profile to suppress the neighbour modes (as indicated in figure 1). The central wavelength shift was realized by varying the microchip temperature. The emission spectra were recorded with a grating monochromator with a maximum resolution of 0.02 nm, corresponding to 600 MHz. The measurement results are shown in figure 4. The emission wavelength is centred at 1079.6 nm and the linewidth is 500 MHz. We believe the measured linewidth was limited by the resolution of the monochromator. At room temperature (T = 22 °C) two longitudinal modes occur, which are shown...
Figure 5. Wavelength tuning of the Nd:YAP microchip laser by temperature.

Figure 6. Setup of the double-pass amplifier arrangement.

in figure 4 by the red line. In this case, these two modes, located quasi-symmetrically with respect to the centre of the gain profile, yield a comparable gain. The measured wavelength difference between the two modes was 0.59 nm, which corresponds to the mode spacing of our 500 µm long microchip resonator ($\Delta \nu = 155$ GHz).

In order to maintain SM operation during wavelength tuning over the whole laser gain bandwidth, the longitudinal mode spacing of the microchip laser has to be exceeded to satisfy the condition of $\Delta \nu \geq \Delta \nu_0$. It can be obtained by shortening the cavity length. But a short microchip will result in a high laser threshold and low optical conversion efficiency, which is induced by poor pump power absorption. To ensure both sufficient pump power absorption and SM operation, a Nd:YAP microchip with a moderate thickness of 310 µm was used. Its longitudinal mode spacing was 250 GHz, corresponding to $\Delta \lambda = 1$ nm. Pumping with 1 W LD, maximum output power of 95 mW was obtained. By changing the temperature of the microchip, continuous wavelength tuning over 0.9 nm was obtained (the temperature was changed in the range of 40–110°C). During the whole tuning range the master laser worked always in SM. A mode hop was observed at 40°C. In figure 5 the shift of wavelength versus temperature is depicted. The wavelength tuning coefficient was estimated to be $d\nu/dT = 0.014$ nm K$^{-1}$, which is in good agreement with the theoretical calculation given in section 1 ($d\nu/dT = -3.3$ GHz K$^{-1}$, corresponds to $d\lambda/dT = 0.013$ nm K$^{-1}$).

3.2. Power amplifier arrangement

Figure 6 shows the scheme of the complete SM Nd:YAP MOPA system. It consists of a microchip master laser and two amplifier discs. The master Nd:YAP laser has described in detail in section 3.2. The amplifier discs used in the setup have a length of 5 mm and a diameter of 8 mm. These two Nd:YAP discs were longitudinally pumped by the fibre-coupled LD (SDL-3460) with a maximum output power of 16 W and a central wavelength of 807 nm. In order to enhance the system amplification, the pump surface was highly reflective at 1.08 µm and highly transmitting at 807 nm and the output surface had an anti-reflective coating for 1.08 µm. Thus, the amplifiers could operate in a double-pass way with a V-shape scheme. To get a good mode overlap between the input light at 1.08 µm and the pump light at 807 nm inside the amplifier discs, Kepler telescopes were used.

Using the master laser with 310 µm cavity length, the SM output power was amplified to 900 mW by our double-pass amplifiers. The $M^2$-number was better than 2.3. The output power versus the LD drive current is shown in figure 7. After the first disc amplifier a maximum output power of 323 mW was achieved with an incident power of 80 mW. It corresponds to an amplification factor of 4. The amplified beam after Amplifier I was used as the input beam for the second amplifier disc. The maximum output power after the two amplification stages was 900 mW. The total amplification was 11.25.

Therefore, a continuously tunable SM Nd:YAP laser system with near 1 W output power and 0.9 nm wavelength tuning range was demonstrated. When the master laser was used instead of the microchip laser with 500 µm wavelength length, a SM operation with 1.43 W output power was obtained. The working temperature of the microchip master laser was fixed at 39°C.

4. Conclusion

A longitudinally LD-pumped Nd:YAP microchip master oscillator power amplifier (MOPA) laser system emitting radiation at wavelength 1.08 µm was demonstrated.
The advantages of Nd:YAP as a laser material are the broad wavelength tuning range, high allowed Nd-doping concentration and the absence of thermally induced birefringence. The Nd:YAP MOPA system consists of a longitudinally LD-pumped monolithic Nd:YAP microchip laser and a two-stage disc amplifier. Single-frequency operation was obtained by using a microchip master laser with short length. Good beam quality was achieved by careful design of the pump and laser mode matching. When using a microchip master laser with a length of 500 µm, 1.43 W output power in SM was generated. To tune the wavelength of the SM MOPA system within the gain profile over 0.9 nm, a 310 µm-long Nd:YAP microchip master laser was used. By varying the working temperature of the master laser, a continuous wavelength tuning was obtained. During the wavelength tuning only one longitudinal mode was observed. The MOPA laser system can be used either in spectroscopy research or as a seeder in high-power SM laser systems.

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References