External-Cavity Tapered Semiconductor Ring Lasers

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Laser operation of a tapered semiconductor amplifier in a ring-oscillator configuration is presented. In first experiments, 1.75 W time-average optical output power has been achieved at room temperature. Results for different configurations and feedback ratios are shown and compared to the output characteristics of the same device in a master-oscillator power-amplifier configuration. Dynamical analysis of the optical signal reveals passively mode-locked operation. The repetition rate of the generated pulses of 214 MHz is determined by the round-trip time of 4.67 ns. Fourier-transformation of the frequency signal to the time-domain yields a pulse-duration of less than 80 ps.

1. Introduction

Tapered travelling-wave laser-amplifiers usually are part of a master-oscillator power-amplifier setup. Typical for such devices is the very low reflectivity of the facets, which is in the range of $10^{-4}$. Besides the use of anti-reflection coatings, bent ridge-waveguides, which hit the facet under a tilt angle with respect to the normal, can be utilized to lower the residual reflectivity [1]. On the other hand, the same kind of device is often designed as a laser oscillator with a linear resonator, by applying mirrors in the form of coatings with higher reflectivities [2], DBR-mirrors [3][4], or by external mirrors which can be realized also in a wavelength selective version, using a grating in order to make the laser tunable [5]. Beyond that, the use of a tilted-stripe traveling-wave optical amplifier in an external-cavity ring laser setup has already been demonstrated [6].

Instead of a traveling-wave optical amplifier with stripe-geometry, we used a device having a tapered gain region in a ring laser setup. The astigmatism, or with other words, the position of the internal virtual source of a tapered amplifier strongly depends strongly on its saturation. With the setup presented here, an image of the internal virtual source is projected onto the input facet of the amplifier, which acts as a spatial mode filter. With a suitable alignment, only the emission of the highly saturated amplifier is efficiently coupled back into the amplifier. By that way, a saturable absorption mechanism is established. It is important to note, that this is only possible for the ring-resonator configuration of a tapered amplifier but not for any kind of linear resonator nor for stripe-geometry amplifiers in a ring resonator. The described behaviour is quite analog to kerr-lens mode locking (KLM) which is commonly utilized for the passive mode locking of solid-state lasers.
2. Device and Setup

Fig. 1: Setup of the ring oscillator configuration with a tapered semiconductor laser amplifier. The aspherical lenses at the left ($f = 4.5 \text{ mm}$) and at the right side ($f = 6.5 \text{ mm}$) of the amplifier are collimating the beam in the fast-axis direction, which is perpendicular to the drawing plane. The cylindrical lens with a focal length of 100 mm is necessary to compensate the astigmatism of the amplifier and to collimate the beam in the slow-axis direction.

Figure 1 shows the schematic diagram of the ring-oscillator setup. The laser active device is a 2.5 mm long tapered semiconductor amplifier with a 500 µm-long and 3.5 µm-wide ridge waveguide. The maximum gain of the amplifier at room temperature is at 920 nm. The geometrical round-trip length of the resonator is 1260 mm. By a Faraday isolator, clockwise circulation is ensured, which is essential, as only the broad output facet of the amplifier, which is orientated to the right side in Fig. 1, can withstand high optical powers of several watts, due to its width of 210 µm. The laser light which is emitted from this facet is collimated in the direction of the fast axis, which is perpendicular to the drawing plane, by a collimating lens system with a focal length of 6.5 mm and a high numerical aperture of 0.615. Because of the astigmatism of the tapered gain region, the vertically collimated beam is convergent in the horizontal direction and forms an intermediate focus there. At an adequate distance right after the intermediate focus, a 100 mm focal length cylindrical lens is located, in order to collimate the beam also in the horizontal direction. With a beam-splitter a 16.5% fraction of the optical power is branched off in order to be fed back into the amplifier. The reflected beam is passing through a Faraday isolator and by two gold mirrors directed versus the input facet, to which the beam is focussed by a 4.5 mm-focal-length aspherical lens with a numerical aperture of 0.55. The bent ridge waveguide in the input section of the device meets the input facet under 4.5°, thus the incident angle of the beam has to be 15° due to the waveguide’s high effective refractive index.

One severe practical problem is regarding the alignment of the optical components. Namely, that the beam can not be observed inside the resonator with a detector card, camera or scanning-slit system. With such a optical barrier inside the resonator, the amplifier
will switch to its non-feedback operation mode, where amplified spontaneous emission is dominant and the beam propagation is completely different compared to laser operation. In order to overcome that problem, we first coupled a signal from a master-oscillator into the amplifier, to perform an alignment and suitable collimation of the emitted beam. All optical components except Mirror 1 can be positioned and adjusted by that way. In a final step, the addition of Mirror 1 and its alignment can be performed easily.

3. Experimental Results

3.1 Quasi-statical behaviour

At first, the optical output of the ring oscillator was measured with a thermophile power detector. Despite this kind of detector is quite reliable for the measurement of optical powers of several watts, it has a multi second response time, therefore the optical powers which are presented in this subsection should always be mentioned to be long time averaged. Additionally, in Subsection 3.2 the results of the experimental investigation of the dynamical behavior will be presented.

As the threshold current depends on the feedback ratio, this can be affected by the use of beam-splitters with various splitting ratios. Figure 2 shows that for two different reflection ratios of 16.5% and 4%. For the lower reflectivity, we observed a less stable operation that led to deviations in the corresponding graph. The tapered amplifier has

![Graph](image)

**Fig. 2:** Output characteristics with different beam splitting reflectivities.

also been characterized in a master-oscillator power-amplifier setup, where the emission of a single-mode ridge-waveguide laser has been used as an input signal. In Fig. 3 this
output characteristics with an optical input power of 10 mW is compared to that of the ring-oscillator setup. To demonstrate that the feedback was not established by any kind of a parasitical linear resonator, we interrupted the feedback path at different locations and measured the optical output with no feedback, which was constantly low in all cases. The corresponding graph in Fig. 3 reveals the difference to the case with feedback.

Fig. 3: Comparison of the optical output characteristics of the tapered laser in a master-oscillator power amplifier setup, and the same device in a ring laser configuration.

3.2 Dynamical behaviour

Because of the anticipated high repetition rate and low pulse duration time, the time dependency can not simply be observed by a normal oscilloscope. Furthermore the lack of a trigger signal makes this measurement even more difficult. To decide whether the laser is running in constant-wave or pulsed mode, the electrical signal from a photodiode was analyzed with respect to its spectral behavior.

As Fig. 4 shows, this analysis reveals a distinct equidistant spectral coverage with harmonics over the whole measurement range from 0 to 20 GHz. The limitation to 20 GHz is due to the measurement-setup. For this measurement, the averaged optical power was 1.05 W at a current of 3.5 A. Harmonics can be observed over a wide range of different currents. The adjustment of the resonator was performed in order to achieve a high averaged optical power and distinct harmonics over the whole spectral range at the same time. Generally, the distribution and intensity of the harmonics depends on the adjustment of the feedback coupling. The separation of the different harmonics of 214 MHz corresponds to an optical round-trip length of 1.40 m. The spectral signal is Fourier-transformed to
4. Conclusion and Discussion

For the first time, the use of a tapered semiconductor laser-amplifier, in a quite simple setup as a ring-oscillator and its capability of generating pico-second laser pulses by passive modelocking is demonstrated. The presented characteristics should be regarded as "first results". From the averaged optical output power of 1.05 W, an amplified spontaneous emission power of 0.15 W and a duty cycle of less than 1:58, the peak power can be estimated to be at least 50 W, considering the fact that the measured pulse duration is limited by the bandwidth of the employed photo-diode. As a limiting factor for the real pulse duration time, the dispersion which is introduced by the amplifier should be mentioned and possibly compensated in a more improved setup. Together with the high spatial beam quality of tapered laser devices, the high peak power makes such a system an interesting laser source for the generation of pulses and second harmonic generation.
References


