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High-speed Er-doped $LiNbO_3$ waveguide lasers

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1 Introduction

In the last few years Er-doped lasers in $LiNbO_3$ operating around 1.56 μm wavelength have attracted considerable attention. The combination of the amplifying properties of erbium with the excellent electrooptic, acoustooptic and nonlinear optical properties of $LiNbO_3$ has led to the development of a whole new family of laser devices of higher functionality [1].

Modelocked Ti:Er:$LiNbO_3$ waveguide lasers of high pulse repetition rate are attractive devices for high speed digital optical (RZ-type) data transmittion in the 3rd telecommunication window. They can be actively modelocked using a monolithically integrated electrooptic phase- (or amplitude-) modulator as the modelocker inside the laser cavity [2]. By modulation synchronous with the fundamental [2] or with harmonics [3] of the axial mode frequency spacing of the laser cavity a comb of axial modes is phase locked leading to a train of short optical pulses in the time domain.

Harmonic modelocking in a long cavity allows to combine efficient pump absorption in the Er-doped waveguide with the generation of pulses of high reptition frequency. Moreover, pulses can be shortened in comparison with fundamental modelocking [4].

However, harmonically modelocked lasers usually emit more than one comb of axial modes (called supermode) causing high frequency noise [5]. In section 2, Ti:Er:$LiNbO_3$ waveguide lasers will be discussed which have been stabilized on a single supermode.

Er:$LiNbO_3$ is also a very attractive material for Q-switched waveguide lasers. Its long fluorescence lifetime is a prerequisit for a high energy storage capability and the incorporation of Er up to the solid solubility limit without fluorescence quenching [6] leads to an efficient power conversion from a diode pump to the Q-switched output. Such a laser emitting pulses of high peak power at wavelengths beyond 1.4 μm is a promising source, e. g. for laser RADAR applications in the eye-save spectral range and as the pump for nonlinear optical frequency conversion into the mid infrared region.

In section 3 Q-switched waveguide lasers with an interferometric switch of high extinction ratio will be discussed.

Finally, section 4 will conclude the paper with an outlook for future activities.

2 Modelocked waveguide lasers

The basic structure of our FM-modelocked waveguide laser consists of an Er-diffusion doped, Ti-diffused waveguide Fabry Perot with a coplanar stripe (CPW) travelling wave electrode on top of the waveguide as the phase modulator [3] (FM-modelocker). Besides this basic structure additional components are required to achieve harmonic modelocking of high amplitude stability. They are discussed in the next subsection.

Laser design: Several methods for the stabilization of a single supermode have been reported for fibre lasers. E. g. intracavity filtering with a Fabry Perot has been successful [7]. Contrary to this high finesse transmission type filter we coupled the active laser cavity to a passive Fabry-Perot of low finesse operated as a reflection type filter. This concept has the potential for a monolithic integration. Depending on the free spectral range of the filter Fabry-Perot modelocking at different harmonic orders can be selected. Up to now 5th [9] and 10th harmonic [10] modelocking at about 5 and 10GHz pulse repetition frequency, respectively, have already been demonstrated using waveguide lasers on Z-cut $LiNbO_3$. As an example, for 10th harmonic modelocking the reference cavity of about 10GHz free spectral range has been glued to the rear end of the laser cavity of about 1GHz free spectral range. The reflectances of the filter cavity of 75 and 30%, respectively, result in a finesse of about 4.3 which is sufficient for the stable selection of one supermode and the suppression of the others. Details of the fabrication of the laser, its Er-diffusion doping, Ti-diffused waveguide structure, SiO_2-buffer layer, electro-plated Au-electrodes and dielectric cavity mirrors are given in [10]. In addition to the CPW-modelocker electrodes 2 lumped electrodes at both ends of the active cavity have been provided for low frequency push-pull phase modulation. This step together with feedback controlled pumping [8] reduces the relative intensity noise (RIN) at the relaxation oscillation frequency during modelocking by about 40dB[9].

The laser has been pigtailed directly to the common branch of a fiberoptic wavelength division multiplexer (WDM) and finally packaged including temperature stabilization, optical isolation and two fibre optic power splitters to extract besides the main output two tap outputs (1% and 9%), one for spectral monitoring and another one for feedback controlled pumping.

Single supermode operation and pulse properties: For 10th harmonic modelocking 29 dBm of rf-power at 9.93 GHz has been fed to the modelocker. To monitor the supermode stabilization the output pulses have been detected using a fast photodiode and fed to an rf-spectrum analyzer. Simultaneous oscillation on more than one supermode results in strong electronic beat components (side modes) at frequencies which are integers of the axial mode spacing apart from the modelocking frequency.

The output of the coupled cavity laser has been compared to the output of the modelocked laser without reference cavity. The side mode supression ratio (SMSR) has been drastically improved from -8 dB to about -55dB for the coupled cavities. The output of the laser has been investigated furthermore by measuring the autocorrelation and the optical spectrum with a resolution of 0.08 nm. At a drive frequency of 9.930 GHz the smallest pulse width of 4.4 ps has been measured. Together with the spectral width of 0.82 nm a time bandwidth product of 0.44 results - indicating that the Gaussian-shaped pulse is chirp-free.

Such a modelocked laser has been successfully used in 10Gbit/s soliton-type data transmission over highly dispersive standard single mode fibre at 1.562μm wavelength [13]. In a back-to-back configuration the critical 10^{-9} bit-error-ratio (BER) has been achieved with only -36.5dBm received optical power. Without any inline filtering and dispersion control this critical BER-figure could be maintained after up to 5 amplified fibre spans of 40km each.

Besides supermode stabilization the filter Fabry-Perot can serve as a repetition rate multiplicator [10]. If the modelocked laser is driven at 5GHz the Fabry-Perot filter of 10GHz free spectral range selects each 2nd harmonic of the generated Fourier spectrum leading to a spectrum with a mode spacing of 10 GHz. The filter suppresses the rf-component at about 5GHz by 28dB compared to the 10GHz-component.

3 Q-switched waveguide lasers

Efficient Q-switched lasers require an intracavity switch of high extinction ratio to prevent CW-prelasing. Waveguide lasers using a directional coupler [11] or coupler-fed interferometer [1] suffered from an insufficient extinction ratio of the Q-switch.

A considerable improvement has been achieved by using a Mach-Zehnder type switch [12] with polarization-insensitive Y-junction as discussed in the next subsection.

Laser design: The Ti:Er:LiNbO$_3$ waveguide laser utilizes a folded intracavity Mach-Zehnder (one Y-junction together with the rear broadband cavity mirror) as the Q-switch. Similar to the modelocked laser, the pump radiation is launched into the waveguide cavity via a fibre-optic WDM and the Q-switched laser emission is extracted in backward direction. The folded interferometer design minimizes the excess loss in the high Q-phase of the laser and allows double pass pumping even during the low Q-phase. The excess loss of the optimized Y-junction of about 0.15dB and the deviation from a symmetric power splitting of < 0.2dB lead to an estimated modulator extinction ratio better than -25dB. In this way a high inversion level of the Er^{3+}-ions can be achieved during the low Q-phase without CW-prelasing.

Details of the Er-diffusion doping, the Ti-diffused waveguide structure, the electrode structure and the cavity design are given in ref. [12]. The most significant difference of the cavity compared to the modelocked lasers is the epoxy-free design of the pump/output coupler which can withstand peak power densities of the Q-switched pulses of several GW/cm^2. A piezoelectrically driven air gap etalon formed by the endfaces of the pump input/signal output fiber (common branch of the WDM) and the polished Ti:Er:LiNbO$_3$-waveguide endface allows to adjust the effective reflectance of this mirror in the range $0.03<R<0.3$. Using this design a fully packaged and diode-pumped Q-switched laser has been realized and operated for several months without problems.

Laser performance: With diode pumping threshold figures of about 90mW and slope efficiencies up to 22% have been achieved for σ-polarized emission at 1562nm wavelength. The modulator has been operated with a DC-bias voltage to give maximum optical extinction and an AC-square wave switching voltage of amplitude V_π and about 5% duty cycle in the frequency range 1kHz $< \nu <$ 5kHz. No evidence of CW-prelasing could be identified. Recently, peak power levels up to 2.5kW have been achieved at 1kHz pulse repetition rate. Build-up of the Q-switched pulses took about 80ns from the leading edge of the electrical switching pulses. With a detector of 1.5GHz bandwidth a periodic fine structure of the Q-switched pulses could be observed. The distance between adjacent peaks under the pulse envelope agrees with the round trip time in the laser cavity indicating the appearance of self-modelocking. The width of the pulse envelope was about 2ns (FWHM).

Such a laser emitting short pulses of high peak power in the eye-save spectral range is an interesting source for laser RADAR applications and for nonlinear optical frequency conversion.

4 Conclusions

Coupled cavity harmonically modelocked waveguide lasers have been demonstrated to generate single super-mode pulse trains of excellent amplitude stability. Repetition rate doubling could be an interesting technique to increase of the modelocking frequency considerably beyond 10GHz which is one of the goals for the future. A further goal will be the monolithic integration of a modelocked laser with an external encoding modulator.

For the Q-switched waveguide lasers a wavelength selective DBR-cavity would be desirable. Such a laser would have a more stable and narrow linewidth emission and render possible the monolithic integration with quasi-phasematched parametric frequency converters of high efficiency.

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