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Invited Paper

Modelocked and Q-switched Ti:Er:$LiNbO_3$ waveguide lasers

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ABSTRACT

Er-diffusion doped $LiNbO_3$ is an excellent electrooptic material for active integrated optics. With low loss Ti-diffused waveguide structures and electrooptic intracavity phase- or amplitude modulators modelocked waveguide lasers with pulse repetition rates beyond 10GHz and Q-switched lasers with pulse peak power levels in the kW-range have been realized. Both types of lasers have been diode-pumped and fully packaged.

Harmonic modelocking allows to combine high pulse repetition rates with high peak power levels. Such a laser has been successfully used as key component of a transmitter for nonlinear optical RZ- (soliton-) type data transmission at 10Gbit/s. Concepts for the stabilization of a single supermode emission as prerequisite for pulses of high amplitude stability and low timing jitter and hence for low error rate transmission are discussed in detail.

Results of Q-switched laser operation with folded Mach-Zehnder type switch of high extinction ratio are presented and potential applications of such a source emitting in the eye-save wavelength range discussed.

Keywords: $LiNbO_3$, integrated optics, Er-doping, waveguide lasers, pulse generation, modelocking, Q-switching

1. INTRODUCTION

During the last years Er-doped devices in $LiNbO_3$ operating in the third telecommunication window around 1.55 μm wavelength have attracted much attention. The combination of the amplifying properties of the dopant erbium with the excellent electrooptical, acoustooptical and nonlinear optical properties of the waveguide substrate, $LiNbO_3$, allows the development of a whole new family of laser devices of higher functionality. By intracavity monolithic integration of modulators and wavelength filters modelocked[1] , Q-switched[2] and tunable lasers[3] have already been demonstrated. The incorporation of Er up to the solid solubility limit without fluorescence quenching[4] is a prerequisit for the development of lasers of efficient power conversion. Fixed photorefractive gratings allow the fabrication of integrable narrow linewidth distributed Bragg reflector (DBR-) lasers simply by holographic writing techniques[5].

In this paper the state-of-the-art of Er-doped integrated optical modelocked- and Q-switched lasers in $LiNbO_3$ is reviewed. In section 2 the realization and the properties of harmonically FM-modelocked waveguide lasers are discussed. In section 3 recent results of Q-switched waveguide lasers with monolithically integrated interferometric switch are presented.

2. MODELOCKED WAVEGUIDE LASERS

2.1 Introduction

Modelocked laser sources of high pulse repetition rate are attractive devices for high speed digital optical (RZ-type) data transmittion. Actively modelocked sources allow the synchronization to an external clock and hence facilitate the interfacing with transmission terminal equipment. Ti:Er:$LiNbO_3$ waveguides allow the monolithic integration of an active modelocker by incorporation of an electrooptic phase- (or amplitude-) modulator in the cavity of a simple Fabry-Perot-type waveguide laser. By modulation synchronous with the fundamental[1] or with harmonics[6] 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[7].

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Using diode-pumping at 1480nm wavelength modelocking has already been demonstrated with waveguide lasers in both, X- and Z-cut $LiNbO_3$ substrates[1,6]. Devices in Z-cut material profit from the slightly lower waveguide attenuation and a higher gain but require an insulating buffer-layer below the modulator electrodes to prevent excess absorption losses. The design of such a laser in Z-cut $LiNbO_3$ is schematically shown in Fig. 1.

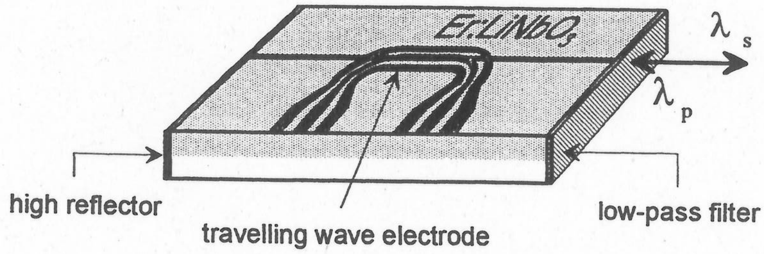

Fig. 1: Schematical structure of a Fabry-Perot type Ti:Er:$LiNbO_3$ waveguide laser with monolihtically integrated intracavity travelling wave phase modulator as active modelocker.

To allow efficient phase modulation at different harmonics of the axial mode frequency spacing a broadband travelling wave type modulator with thick electro-plated coplanar wave (CPW) microstrip Au-electrodes has been used. Details of the fabrication of the waveguide and the laser cavity can be found in [6].

By adjustment of the output coupling strength of the laser cavity modelocked operation has been achieved at a number of different wavelengths: 1531nm (π-polarized; E||c), 1545nm (π), 1562nm (σ; E$\perp$c), 1575nm (π), 1602nm (π), 1611nm (σ). Threshold figures as low as 9mW and an average output power of 1.1mW (at 75mW pump power) have been achieved at λ=1602 nm (slope efficiency: 1.6%).

The highest output power (up to 12mW average average power) and slope efficiency (14.4%) has been observed at 1575nm wavelength[8]. Time-bandwidth-products close to the transform limit of Gaussian pulses (0.44) have been determined. With fundamental modelocking at 1602nm wavelength and 1.281GHz repetition frequency pulses of 8.6ps width (FWHM) and 650mW peak power have been achieved[6]. With harmonic modelocking the pulse width could be further reduced. As an example, at the third harmonics (3.843GHz) pulses of 3.8ps width (FWHM) and 630mW peak power could be generated. Harmonic modelocking has been observed up to the 10th harmonic (10GHz pulse repetition frequency), limited only by the available RF-signal generator.

In the last years a major effort has been made to stabilize the performance of the integrated modelocked lasers as two phenomena can seriously degrade the amplitude stability of the modelocked pulses:

1) Low frequencies noise around several hundred kHz arising from relaxation oscillations[9].

This issue which is common to fundamentally as well as harmonically modelocked lasers can be almost eliminated by feedback controlled pumping of the Er-laser[8].

2) High frequency amplitude noise in the MHz through GHz range which can be a serious issue for harmonic modelocking[10].

2.2 Stabilization concepts

2.2.1 Low frequency noise suppression

To suppress relaxation spiking during modelocking a correction component to the injection current of the pump laser diode is derived by an electronic circuit to achieve controlled pumping[6]. About 40dB reduction of the spectral power density at the dominant peak of the low frequency (up to 1MHz) noise spectrum is achieved routinely. Another low frequency noise contribution of the FM-modelocked laser -- the competition of the two interleaved pulse trains[7] -- can be suppressed by a careful adjustment of the drive-frequency. The additional application of a sine-wave to lumped electrodes at both ends of the Fabry Perot cavity (see Fig. 3) for push-pull phase modulation at about 5MHz further reduces the low frequency noise . In Fig. 2 the measured relative intensity noise (RIN) of a waveguide laser operated under feedback controlled diode-pumping and 5th harmonic modelocking (4.998 GHz) is shown versus frequency. The range up to 10MHz has been expanded for clarity. Besides the relaxation oscillation peak additional (lower) peaks are visible which result from the intracavity push-pull modulation at 5MHz. Above 40MHz the RIN-figure is close to the shot noise limit. The graph on the bottom corresponds to the sensitivity limit of the spectrum analyzer.

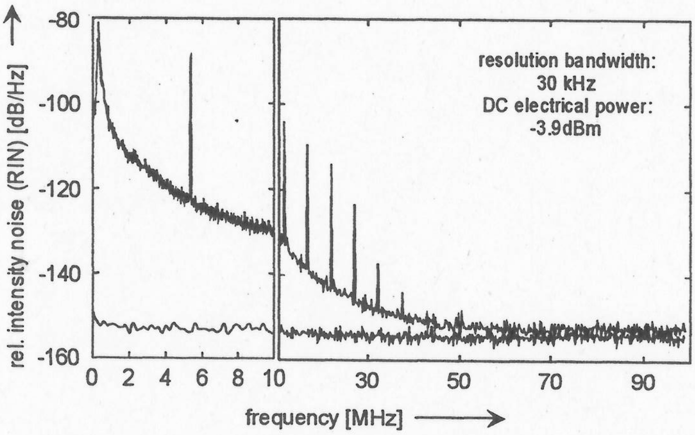

Fig. 2: Relative intensity noise versus frequency of a harmonically modelocked waveguide laser during feedback controlled diode-pumping. The electrical power of average detector signal and the resolution bandwidth of the spectrum analyzer are given in the diagram.

2.2.2 High frequency noise suppression

During harmonic modelocking axial modes are coupled which are an integer multiple of the axial mode spacing apart. According to the harmonic order the laser can oscillate on a number of different combs of axial modes so called supermodes[10]. The uncorrelated superposition of supermodes leads to pulse amplitude fluctuations. To eliminate this problem the laser has to be stabilized on a single supermode.

In a linear standing wave (Fabry Perot-) cavity the supermodes produce a standing wave pattern in the collision regions of the counterpropagating pulses (note, that the number of circulating pulses is equal to the harmonic order of modelocking). The different supermodes are coupled by the time dependent spatial hole burning in these collision regions[10].

There are two different approaches to decouple the supermodes: local Er-doping leaving the collision regions undoped as already proposed by Becker et al. in 1972 for harmonic modelocking of the Nd:YAG-laser[10] and intracavity push-pull phase modulation to destroy the spatial hole burning as successfully applied to Fabry-Perot fibre lasers to force them to continuous single mode operation[11].

Both methods are not sufficient to force the harmonically modelocked Ti:Er:$LiNbO_3$ waveguide laser to a stable single supermode operation. Up to 20dB side mode suppression ratio (SMSR) between the detector signal at the different beat components of the competing supermodes and the dominant component at the modelocking frequency has been obtained. Obviously, the amplified spontaneous emission noise of the laser is sufficient to cause the laser to jump between adjacent supermodes.

Instead of decoupling the supermodes the active stabilization of one supermode is required for a long term stable operation.

In fiber ring lasers this stabilization has been achieved by intracavity filtering[12]. But, due to the very fine granulation of the axial mode eigen frequencies high finesse filters had to be used[13].
In integrated Fabry Perot type lasers the mode spacing is in the GHz-range allowing efficient intracavity mode selection with comparatively low finesse filters.
In the following the design, the fabrication, and the properties of a coupled cavity type single supermode harmonically modelocked laser are discussed in more detail.

2.3 Laser fabrication

Waveguide lasers offer the possibility to couple the active Fabry Perot cavity directly to another passive Fabry-Perot cavity of the same substrate material. In principle, this could we done in a monolithic approach using integrable (DBR-type) reflectors. First encouraging results have been achieve by hybridly coupling the active cavity to a passive one[14]. Both, coupling of the passive cavity to the active one on the pump input side and on the rear high reflector side of the active cavity have been successfully tried. As an example the stabilization at the 5^{th} harmonic with a passive reference cavity coupled to the pump input side is shown in Fig. 3 on the left.

To fabricate the active laser cavity the Z-cut $LiNbO_3$ sample has been doped by indiffusion of a 30 nm thick layer of vacuum-deposited erbium at 1130 °C during 150 h. Afterwards photolithographically defined 7 μm wide and 93 nm thick Ti-stripes have been indiffused at 1060 °C during 8.5 h to form the 66 mm long active intracavity waveguide structure.

The active cavity is comprised of a broadband high reflector on the rear side and a glued passive waveguide Fabry-Perot of 4.985 GHz free spectral range with mirror reflectivities of 30% (dielectric low pass filter) and 4% ($LiNbO_3$-fibre transission), respectively.

The modelocked laser is pumped by a broadband high power laser diode with a central wavelength of 1480 nm through a fiberoptic wavelength division demultiplexer (WDM) which allows to extract the modelocked laser emission in backward direction (as indicated in Fig. 3 on the left). Up to 140 mW of pump power was available in the common branch of the WDM. For σ-polarized pumping the laser emits in σ-Polarisation at the wavelength 1562 nm.

The free spectral range of the reference cavity almost coincides with the modelocking frequency. The resulting modulated effective reflectivity of the output coupler mirror of the active laser cavity favours the laser oscillation on one supermode and suppresses the others. Using this concept stable single supermode operation with a side mode suppression ratio (SMSR) > 60dB over a long term (hours) has been achieved (see diagram in Fig. 3 on the right).

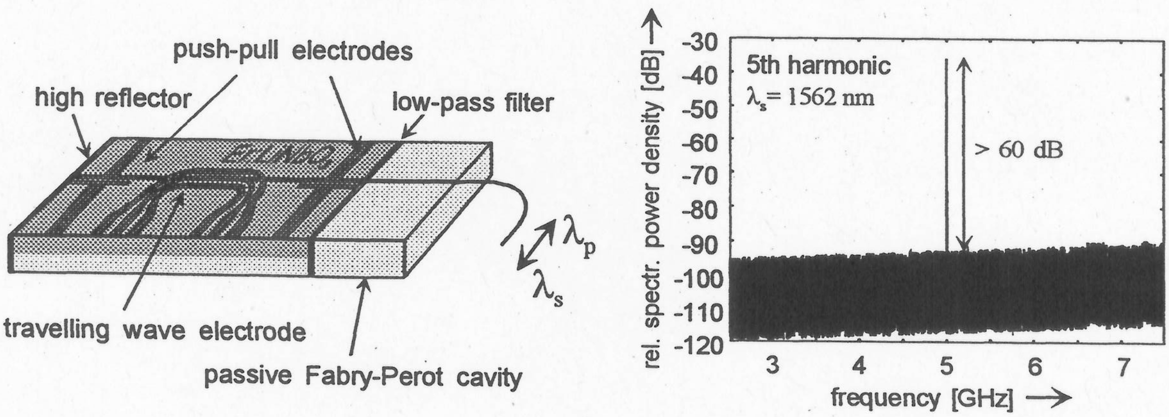

Fig.3 : Coupled cavity modelocked Ti:Er:$LiNbO_3$ waveguide laser (left). Electronic spectrum of the detected pulse train for 5th harmonic modelocking (right).

Due to the large free spectral range (999.6MHz) of the integrated laser the supermode stabilization has been achieved with a low finesse (≈ 2.3) reference cavity in contrast to modelocked fiber lasers where the small axial mode spacing requires a high finesse (≈ 50) intracavity filter[13]. With push-pull phase modulation via the additional lumped electrodes on both ends of the active laser cavity and with controlled pumping the relative intensity noise of the laser reaches almost the shot noise limit for frequencies above 40MHz.

2.4 Pulse properties

An optical autocorrelator for measurements of the pulse width in the time domain and an optical spectrometer of about 0.1nm resolution for measurements of the pulse spectra have been used. In Fig. 4 on the left the autocorrelation trace for

5th harmonic modelocking is shown. Assuming a Gaussian pulse shape a pulse width (FWHM) of 15.4ps can be deconvolved from the width of the correlation trace. On the right the corresponding optical spectrum of 0.33nm width is shown. From both results a time-bandwidth-product of 0.62 can be calculated indicating that the pulses are slightly chirped.

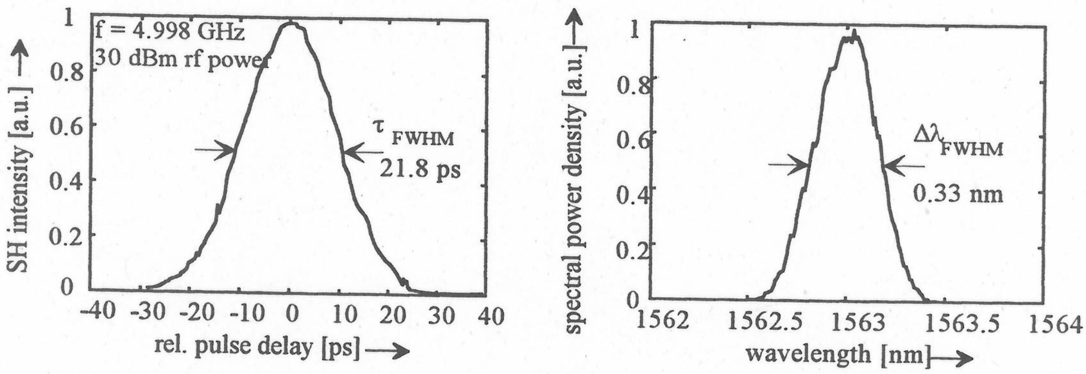

Fig.4: Left: Autocorrelation trace as optical second harmonic (SH-) intensity versus relative pulse delay for 5th harmonic modelocking; the rf-power level incident on the travelling wave phase modulator (modelocker) was 30dBm. Right: corresponding optical spectrum.

Using a scanning Fabry Perot as high resolution optical spectrum analyzer the eigenmodes of a single supermode could be resolved and no jumps between adjacent supermodes were observed when the temperature of the laser was adjusted properly.

2.5 Applications

Modelocked lasers are potential sources for high bit rate digital optical transmission. Especially, higher peak power levels of modelocked pulses compared to externally modulated continuous wave lasers are attractive for nonlinear optical (soliton-type) data transmission in the 3rd telecommunications window to upgrade existing highly dispersive fiber links. A diode pumped, fully packaged harmonically modelocked Ti:Er: $LiNbO_3$ waveguide laser has been tested for soliton-type data transmission at 10Gbit/s over standard single mode (SI-) fibre (dispersion ≈ 17ps/nm\,km). The laser has been modelocked at the 5th harmonic (4.998GHz) and orthogonal polarization switching has been applied to minimize soliton interaction in the line[15]. In Fig. 5 the bit-error-ratio (BER) is shown as function of the received optical power for a back-to-back measurement of the pulses after data encoding and optical attenuation.

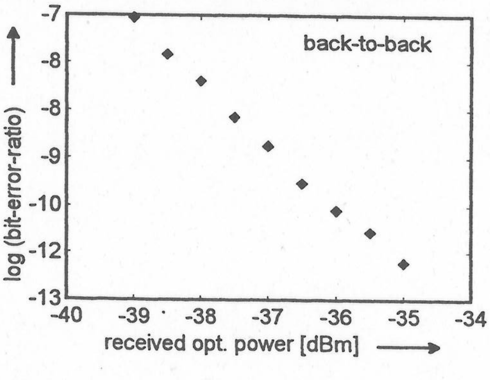

Fig.5: Bit-error ratio (BER) versus received optical power in a back-to-back configuration; the received power has been varied using a fibre-optic inline attenuator.

Only –36.8dBm of optical power is required to remain below the critical BER of 10^{-9}. The data stream of +14dBm average optical power was launched into successive spans (40km each) of SI-fibre followed by an erbium doped fibre amplifier (EDFA) of +14dBm saturated output. Without any inline filtering and dispersion controls a BER of about 10^{-9} has been achieved after 5 amplified fibre spans.

3. Q-SWITCHED WAVEGUIDE LASERS

3.1 Introduction

Diode pumped integrated Q-switched lasers can be efficient, miniaturized sources of short optical pulses suitable for a variety of applications. They could be used as pump sources for parametric nonlinear frequency conversion, as sources for optical time domain reflectometry (OTDR) and for laser-RADAR. For the latter application frequently eye safe sources are recommended. Er-doped Q-switched lasers emitting at about 1.56µm wavelength meet this requirement and have therefore attracted increasing attention in the last years[16, 17]. Among the different possible substrates for Er-doped waveguide lasers $LiNbO_3$ is very attractive. High Er-concentration levels up to the solid solubility limit can be achieved by indiffusion without significant fluorescence quenching. This feature together with the long fluorescence lifetime of the Er-ions guarantee a high energy storage capability and a high power conversion efficiency which can be exploited for the design of efficient Q-switched waveguide lasers. Peak power levels in the kW-range have been predicted[17]. Moreover, due to the excellent electrooptic properties of the $LiNbO_3$ substrate the required intracavity switch can be monolithically integrated[18] leading to a compact and rugged laser design.

The achievable peak power of the Q-switched pulses is limited by amplified spontaneous emission and prelasing (onset of continuous wave lasing even in the low-Q condition of the laser cavity)[19].

A high extinction ratio of the intracavity switch is most important to keep the prelasing threshold as high as possible.
In the following the design and fabrication of a Q-switched laser with an intracavity switch of high extinction ratio is presented.

3.2 Design and fabrication

In Fig. 6 a schematical sketch of the structure of the Q-switched laser and of the setup for its experimental investigation are shown. The laser utilizes a folded intracavity Mach-Zehnder type intensity modulator 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.

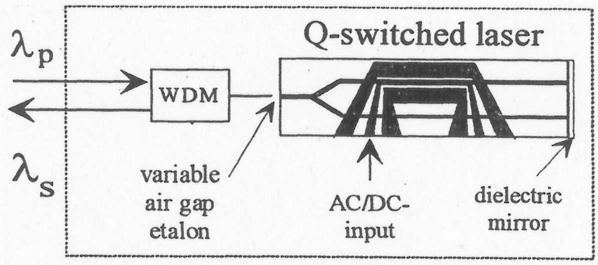

Fig. 6: Schematical sketch of the laser structure and the experimental setup for the investigation of Q-switched laser operation.

The actual device has a length of about 75mm. Half (with respect to the X-direction) of the Z-cut (Y-propagation) $LiNbO_3$ substrate has been doped over the complete length near the surface by indiffusion of 30nm of vacuum deposited Er at 1130°C during 150h. Subsequently, the photolithographically delineated 7µm wide and 100nm thick structure of Ti-stripes has been indiffused at 1060°C during 7.5h to form the waveguide channels. In the undoped region waveguide scattering losses of 0.03dB/cm have been measured. The splitter is a Y-junction with X-sine shaped bends located in the center of the cavity. Its excess loss is about 0.15dB and its deviation from a symmetrical power splitting is below 0.2dB leading to an estimated modulator extinction ratio of better than -25dB. On the waveguide structure an 0.6µm thick insulating SiO_2-buffer has been vacuum deposited prior to the electrode fabrication.
The electrode structure of the intracavity modulator (Q-switch) is a 25mm long symmetrical coplanar microstrip line fabricated by lift-off of a sandwich of sputtered Ti/Au. The modulator has been operated as a lumped device without low resistance termination due to the relaxed bandwidth requirements. The halfwave voltage for the laser polarization TE- (σ-) was about 28V due to the smaller electrooptic coefficient available in this polarization.

The laser has a Fabry Perot cavity comprised of a dielectric mirror vacuum deposited on the rear waveguide endfaces and a variable etalon with air gap. The dielectric mirror has a high reflectance (98%) at both, emission wavelength ($\lambda_s \approx$ 1562nm, σ-polarized or $\lambda_s \approx$ 1575nm, π-polarized) and pump wavelength ($\lambda_p \approx$ 1480nm). In this way double pass pumping is provided allowing an improved pump absorption efficiency. On the other side a variable output/pump coupler mirror has been realized by an adjustable, 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. The effective reflectance of this mirror can be adjusted in the range $0.03<R<0.3$.

3.3 Experimental and theoretical results

Using a pigtailed laser diode ($\lambda_p \approx$ 1480nm) of up to 145mW output power as the pump source a threshold of about 90mW (σ-polarized) has 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-switching voltage (square wave) of amplitude Vπ and about 5% duty cycle in the frequency range 1kHz to 5kHz. No evidence of prelasing could be identified. The Q-switched pulses have been attenuated by 50dB in a cascade of fiberoptic splitters and attenuators to ensure linearity of the detector, a biased PIN-photodiode of 1.5GHz bandwidth. The detector signal has been measured using a scope of again 1.5GHz bandwidth.

Balsamo et al.[19] have numerically simulated the dynamic behaviour of such a laser, based on the following hypotesis:

i) The Er:$LiNbO_3$ system has been approximated as a quasi-two level system
ii) The multi-longitudinal mode laser cavity and the pump dynamics have been represented with the mean field approximation
iii) Three different rate equations have been used to approximate the population inversion in the different parts of the folded MZ-cavity.
The system of N_{mode} + 4 coupled nonlinear differential equations has been solved numerically with an adaptive time-step routine suitable for stiff systems.

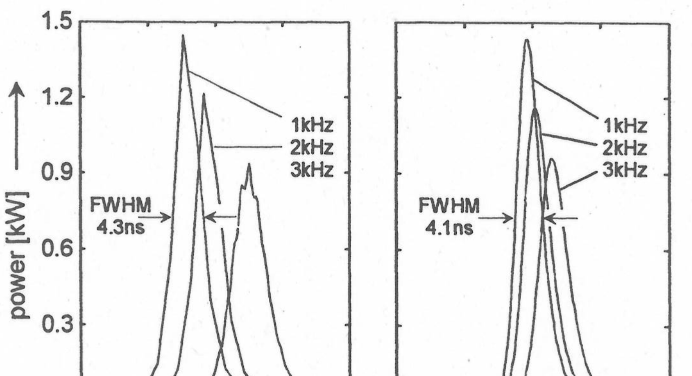

Fig. 7: Output power of a Q-switched Ti:Er: $LiNbO_3$-waveguide laser versus time; left: measured through the pump/output coupler in backward direction. The zero of the abscissa scale coincides with the leading edge of the electrical switching pulse; parameter of the set of graphs is the pulse repetition frequency; right: numerically simulated results for comparison.

In Fig. 7 the experimental (left) and theoretical results (right) of Q-switched operation of the Ti:Er:$LiNbO_3$ waveguide laser are presented for 145mW incident pump power. The zero point of the abscissa of the diagrams correspond to the leading edge of the electrical switching pulse. At 1kHz repetition rate up to 1.44kW peak power has been measured. The build up time is about 165ns and the pulse width is 4.3ns (FWHM). With increasing repetition rate the peak power degrades, the pulse width and the build-up time increase, respectively.

Good agreement between measured and calculated peak power levels and pulse widths has been achieved.

For π-polarized pumping π-polarized emission at 1575nm has been observed with significantly lower peak powers (up to ≈..0W) compared to the σ-polarized emission at 1562nm wavelength.

We also investigated the output spectrum emitted from both endfaces of the waveguide laser. At the maximum pump power level the spectrum emitted on the high reflector side of the cavity is 40-times narrower (FWHM: 2.5nm) than the spectrum detected through the pump coupler and a cascade of fiber components. We attribute this to the generation of Raman shifted light in the fiber. As a result part of the optical power is shifted into a longer wavelength range where the detector sensitivity is reduced. Therefore, with increasing pump power level the ratio of the dectected peak power levels emitted in forward and backward directions increased up to a factor of 1.3. For that reason, in Fig. 7 (left part) the maximum peak power level has to be corrected, i. e. multiplied, by this factor.

Recently, even higher peak power levels have been achieved as shown in Fig. 8 for a repetition rate of 1kHz. For this example the build-up time was reduced to about 80ns. The width of the pulse envelope is about 2ns (FWHM). The distance between adjacent peaks in the fine structure of the pulse agrees with the round trip time in the laser cavity. We attribute the fine structure to self-modelocking of the laser. The highest peak power exceeds 2.5kW.

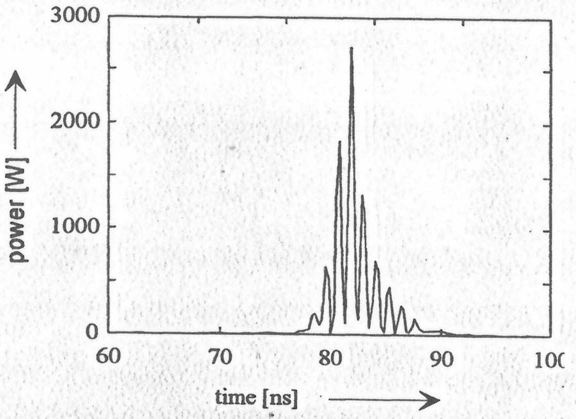

Fig. 8: High resolution scan of the output power of a Q-switched Ti:Er: $LiNbO_3$-waveguide laser versus time

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 nonlinear optical frequency conversion. First results of optical parametric fluorescence with a Q-switched waveguide laser as the pump source will be discussed during the oral presentation.

CONCLUSION

Coupled cavity harmonically modelocked Ti:Er:$LiNbO_3$ waveguide lasers have been demonstrated to generate single supermode pulse trains of excellent amplitude stability (SMSR>60dB at 5GHz). Recently almost the same stability has been achieved at 10 GHz pulse repetition rate. These lasers are fully packaged, pigtailed and diode pumped rack-mountable units. With such a laser as the key component of the optical transmitter soliton type data transmission at 10Gbit/s over 200km of highly dispersive SI-fibre with BER below 10^{-9} has been successfully demonstrated. We are confident to increase the pulse repetition rate further for applications in even higher capacity digital optical transmission links.

Using a folded Mach-Zehnder type intensity modulator of high extinction ratio as intracavity switch diode-pumped Q-switched laser operation with peak power levels in excess of 2.5kW at 1kHz repetition rate has been demonstrated. A laser of this type has already been pigtailed and packaged. It is actually tested for laser RADAR applications and as pump source for nonlinear optical frequency conversion.

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