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Efficient, Diode Pumped, Harmonically Modelocked Ti:Er:LiNbO$_3$-Waveguide Laser for Soliton Transmission

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Abstract: Modelocked laser operation with a stabilized, packaged and diode pumped Ti:Er:LiNbO$_3$-waveguide laser has been demonstrated at 1562 (TE) and 1575nm (TM) wavelength with about 5 GHz pulse repetition rate and 14% slope efficiency (up to 11.4mW average output power).

Introduction

Modelocking is a versatile means to generate pulse trains of high repetition rate and peak power. Therefore, a modelocked laser emitting in the third telecommunication window is regarded as a very promising source for high bitrate soliton RZ-type data transmission. Integrated optical versions of such a modelocked source are rugged and have a high potential for miniaturization. Moreover, sources in electrooptic materials allow a monolithic integration of an active modelocker [1] and in this way the required synchronization to a system clock for digital data transmission.

Er-doped LiNbO$_3$ is an attractive material for the realization of such a modelocked source. It has excellent electrooptic properties, allows the incorporation of Er up to the solid solubility limit without fluorescence quenching and the fabrication of high quality Er-doped waveguides [2]. Using a monolithically integrated intracavity phase modulator as modelocker (FM-type modelocking) and a broadband Fabry Perot waveguide cavity fundamental and harmonic modelocking [3, 4] have already been demonstrated. However, the output power of these lasers was low and the emission wavelength (1531nm, 1602nm) was not matched to the third telecommunication window.

In this paper we report a highly efficient harmonically modelocked waveguide laser of suitable emission wavelengths. Pulse widths between 7 and 21ps and peak power levels up to 310mW have been obtained. The laser is packaged, thermoelectrically temperature controlled and diode pumped. It has been developed for soliton communication experiments in the European ACTS-project ESTHER (AC063).

Device fabrication

Half (with respect to the X-direction) of the Z-cut (Y-propagation) LiNbO$_3$ substrate has been doped near the surface by indiffusion of 28nm of vacuum deposited Er at 1130°C during 125h. Subsequently, photolithographically delineated 7μm wide and 98nm thick Ti-stripes have been indiffused at 1060°C during 8h to form the 66.5mm long waveguide channels. Attenuation figures of the undoped channels down to 0.02dB/cm (TE) and 0.05 dB/cm (TM) have been measured at 1523nm wavelength, respectively. In the doped waveguides almost the same attenuation figures can be estimated from the difference between the measured transmission and absorption. The FWHM-figures of the near field intensity distributions of the modes at 1556nm wavelength are 6.3μm × 4.4μm (width × depth; TE) and 4.6μm × 3.1μm (TM), respectively. Within experimental error the intensity distributions are identical for doped and undoped channels.

To avoid excess losses of the TM-mode an 0.6μm thick insulating SiO$_2$-buffer has been vacuum deposited onto the substrate surface prior to the electrode fabrication.

The electrode structure of the intracavity travelling wave phase modulator (modelocker) is a symmetrical coplanar microstrip line with a gap to hotline width ratio of 0.75. First, a thin electrode has been fabricated by photolithographic lift-off of a sandwich of 30nm sputtered Ti and 120nm sputtered Au. Subsequently, the Au-structure was electroplated up to a thickness of 4.5μm using as a cyanidic Au-electrolyte.

The laser cavity is comprised of a high reflector on the rear side and a pump input coupler of optimized output coupling for the signal (see e.g. [5]). Both mirrors consist of SiO_2/TiO_2-layers directly deposited onto the polished waveguide endfaces using O_2^+-ion assisted reactive evaporation. The rear mirror consists of 13 layers quarterwave at 765nm leading to about 98% reflectivity at both, pump and signal wavelengths. The output coupler constists of 14 layers quarterwave at 946nm leading to a minimurm reflectivity of about 7% at the pump wavelength ($\lambda \approx 1480$nm) and an output coupling of the signal of about 55%.

After characterization of the laser chip the pump input side of the cavity was pigtailed with the common branch of a fiberoptic wavelength division demultiplexer (WDM) to allow coupling of a pigtailed pump laser diode and extraction of the laser output in backward direction. The WDM has standard (9/125µm) fiber pigtails.

Finally, the pigtailed laser has been packaged including optical isolation, thermoelectric temperature control (< ± 0.01K) and two cascaded 10/90% power splitters. FC/PC connection is provided for the pump input, for the laser output (90%), and for two tap outputs (9% , 1%) for monitoring of modelocking stability and pulse peak power and to derive a control signal for feedback stabilization (controlled pumping).

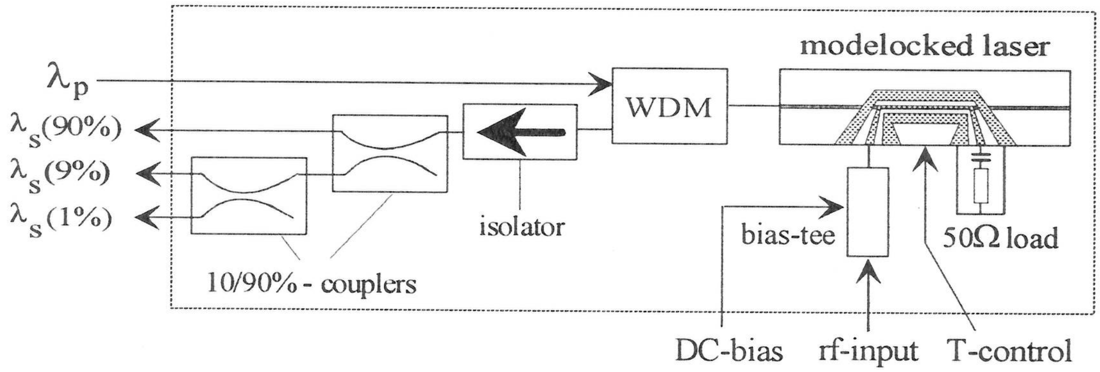

Fig. 1: Schematical structure of the pigtailed and packaged laser.

Experimental results

To determine the halfwave voltage of the intracavity phase modulator the Er-doped waveguide resonator has been operated as an electrooptical spectrum analyzer [6]. As the signal source a DFB-laser diode emitting at 1546nm wavelength has been launched into the Er-doped waveguide cavity. A sawtooth voltage has been applied to the modulator electrodes and the voltage swing between two adjacent resonances of the cavity at the DFB-laser wavelength has been measured in both, TE- and TM-polarization. The measured halfwave voltage V_π was 5.4V for TM and 21.6V for TE, respectively.

The modelocked Er-doped laser has been investigated in terms of axial mode structure, power characteristics, pulse width, spectrum and time bandwidth product for modelocking at two different harmonics (2nd and 5th harmonic) of the axial mode frequency spacing. Especially at the 5th harmonic the laser properties have been carefully investigated. To drive the modelocker the rf-signal from a highly stable generator was boosted using a narrow band low noise amplifier and then fed via a bias tee to the travelling wave electrodes of the intracavity phase modulator. The electrodes are terminated (AC) by a 50Ω load.

To pump the Ti:Er:$LiNbO_3$-waveguide laser a high power laser diode of about 1480nm center wavelength and 12nm spectral width has been used. The pump power was launched through the WDM into the modelocked laser. Up to 140mW of incident pump power were available at the common branch of the WDM.

To determine the polarization dependent axial mode frequency spacing of the waveguide cavity the laser output in cw-operation was detected and the Fourier component at the beat frequency of the axial eigenmodes was determined using an electronic spectrum analyzer. The mode spacing is 994.3MHz for TE- and 1029.5MHz for TM-polarization. This method also provides a very precise determination of the mode effective indices.

In Fig. 2 the cw-power characteristics of the Er-laser is shown for TM(π)-polarized emission at 1575nm and TE(σ)-polarized emission at 1562nm wavelength, respectively. The polarization and wavelength of the emission can be adjusted by the pump polarization. With $\pi(\sigma)$-polarized pumping the Er-laser emits at 1575(1562)nm $\pi(\sigma)$-polarized. Threshold pump power and slope efficiencies are 56mW(65mW) and 14.4%(13.2%) for $\pi(\sigma)$-polarized emission, respectively. Both, slope efficiency and output power are more than an order of magnitude better than previously reported results [3, 4].

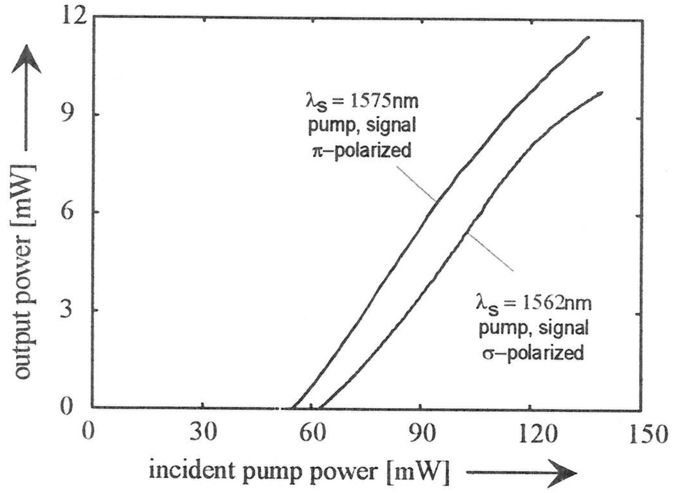

Fig. 2: Output power versus pump power incident at the common branch of the f/o WDM-coupler (see Fig. 1) for both, π- and σ-polarized emission. The polarization dependent emission wavelengths are indicated.

To suppress relaxation spiking of the laser also during modelocking 9% of the laser output were detected and the detector signal fed to a specially designed electronic control circuit. This circuit generates and superimposes a correction component to the injection current of the pump laser diode to suppress relaxation oscillations by controlled pumping. Up to 42dB reduction of the spectral power density at the dominant peak of the noise spectrum has been achieved leading to a relative intensity noise of -82.3dB/Hz for 3.5dBm of DC-electrical power (detector signal into 50Ω; corresponding to 6.7mW of average optical power) at the residual relaxation oscillation peak around 450 kHz. At frequencies above 100 MHz the laser output is almost shot noise limited.

Results of modelocking are shown in Fig.3 for the 5th harmonic and π-polarized emission at two different levels of the rf-drive power. With 29dBm of rf-power a pulse width of 7.4ps (FWHM) has been determined by deconvolution of the autocorrelation trace assuming a Gaussian pulse shape. Together with the spectral width of 0.77nm a time bandwidth product of 0.68 results. Pulse peak power levels up to 310mW have been achieved. For 16dBm of rf-power the pulse width broadens to about 21ps and the spectral width can be estimated to 0.26nm. However, the stability of the pulses is significantly deteriorated as can be seen from the noise on both, the correlation trace and the spectrum in Fig. 3.

For σ-polarized emission at 1562nm wavelength 5th harmonic modelocking has been obtained at 4.97133GHz. Time bandwidth products down to 0.45 have been achieved, but, as a result of the much higher halfwave voltage and the much lower phase modulation index the stability of the pulses was not as good as in the π-polarized case.

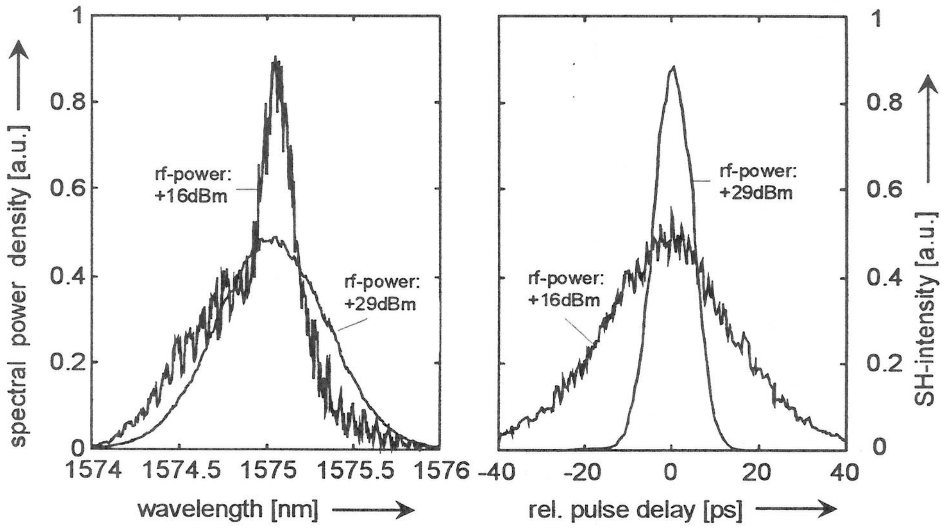

Fig. 3: Spectral power density versus wavelength (left) and autocorrelation trace as function of the relative pulse delay (right) for modelocking at the 5th harmonic (5.14766GHz) in π-polarized emission.

Conclusions

We have demonstrated a harmonically modelocked Ti:Er:$LiNbO_3$-waveguide laser of essentially improved performance compared to former results. Output power and slope efficiency have been improved more than an order of magnitude. The emission wavelength is now suitable for applications in the third telecommunication window. By an improved feedback controlled pumping the RIN of the laser could be reduced by 42dB. Further improvements of the laser seem to be feasible by the development of monolithically integrable low loss Bragg gratings which fix the emission wavelength and allow to tailor the pulse bandwidth and chirp.

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