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Integrated Optical Ti:Er:LiNbO$_3$-Soliton Source

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Abstract: Efficient diode pumped and harmonically modelocked operation of a fully packaged Ti:Er:LiNbO$_3$-waveguide laser at 1562 (TE) and 1575nm (TM) wavelength has been investigated in terms of pulse properties and pulse to pulse amplitude- and timing stability. An external amplitude modulator has been used for encoding of the modelocked pulse train with different bit-sequences. A bit error-rate of about 10^{-10} for a 1-0-1-0 bit sequence has been observed over more than half an hour.

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-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 the monolithic integration of an active modelocker 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 [1]. Using a monolithically integrated intracavity phase modulator as modelocker (FM-type modelocking) and a broadband Fabry Perot waveguide cavity fundamental and harmonic modelocking [2, 3, 4] have already been demonstrated. With harmonic modelocking high pulse repetition rates can be achieved with long laser cavities leading especially for Er-doped lasers to an improved pump absorption and laser output efficiency, respectively.

Using this concept an efficient (14% slope efficiency) diode-pumped and fully packaged harmonically modelocked laser has been demonstrated. In this paper we report the properties of this laser and bit error rate investigations of RZ-type data for soliton transmission achieved by external encoding of the pulsed laser output. The laser will be tested in soliton communication experiments within the European ACTS-project ESTHER (AC063).

Setup of the soliton source

Details of the fabrication of the laser have been reported in ref. [4]. After characterization the laser has been pigtailed and packaged as shown schematically in Fig. 1.

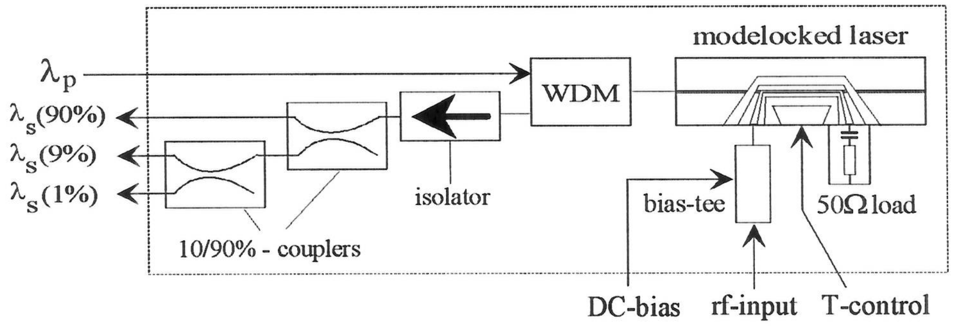

Fig. 1: Schematical structure of the pigtailed and packaged laser.

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. Its signal branch has been optically isolated to prevent feedback induced instabilities. The laser output is further split using two cascaded 10/90% fiberoptical power splitters for monitoring of the modelocking stability, of the pulse peak power and to derive a control signal for feedback stabilization. FC-receptacles are provided for the pump input, for the main laser output (90%), and for the two tap outputs (9%, 1%). The pigtailed laser has been mounted on a thermoelectrically controlled Cu-heat sink allowing an accurate temperature stabilization ($< \pm 0.01$K). All the components mentioned above are assembled in a housing which can be plugged together with other components like the pump laser and the modelock driver into a common 19" rack.

For bit error rate investigations the 90% output port of the laser has been launched through a commercial Mach-Zehnder-type Ti:LiNbO$_3$-intensity modulator for data encoding. The modulator has a halfwave voltage V_π of 4.3V (at 1kHz) and an optical bandwidth (-3dB) of 5GHz. A polarization controller has been used to adjust the input polarization state to TM for maximum extinction ratio (23dB).

Source properties

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 (see Fig. 1). Up to 140mW of incident pump power were available at the common branch of the WDM. 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 $\pi(\sigma)$-polarization, respectively.

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.

Modelocking has been achieved by phase modulation (FM-type modelocking) synchroneously with different harmonics of the axial mode frequency spacing of the laser cavity. Results are shown for the 5th harmonic as the corresponding pulse repetition frequency at about 5GHz is of most interest for the ACTS-project mentioned above. BER-measurements have been carried out at the 2nd harmonic due to actual limitations of the data rate of the available pattern generator.

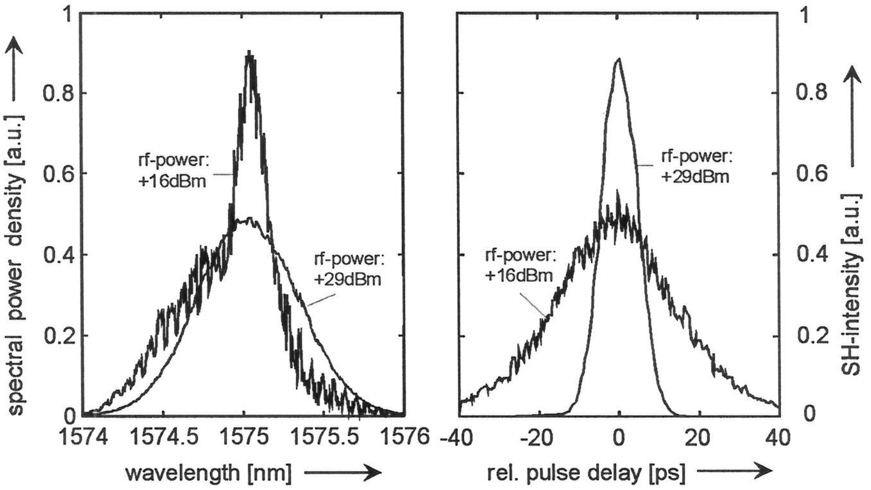

Fig. 2: Spectral power density versus wavelength (left) and autocorrelation trace as function of the relative pulse delay (right) for modelocking at the 5th harmonic (5.14766GHz) in π-polarized emission.

In Fig.2 the laser output pulses are shown in the wavelength and time domain for the 5th harmonic and π-polarized emission at 1575nm wavelength for 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 auto-correlation trace assuming a Gaussian pulse shape. Together with the spectral width of 0.77nm a time bandwidth product of 0.68 results indicating a slight frequency chirp of the pulses. Pulse peak power levels up to 310mW have been achieved which are more than sufficient for soliton generation in dispersion shifted fibers. 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. With 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. During these measurements feedback controlled pumping of the modelocked laser has been used to reduce the low frequency noise as discussed later.
For FM-modelocking two interleaved pulse trains can exist [5] which are synchronized with the positive and negative extremes of the phase modulation, respectively. By fine-tuning of the rf-drive frequency and monitoring the pulse peak and average powers, respectively, we found fairly stable regimes for the operation of either of the two pulse trains with a narrow frequency range (about 50kHz) in between where a strong competition of both pulse trains leads to an enhanced low frequency noise of the laser output power.
To assess the stability of the source for soliton-type data transmission we have launched the main output of the modelocked laser through a Mach-Zehnder-type $LiNbO_3$-modulator and driven the modulator with different NRZ-data-patterns for digital encoding. The encoded output has been detected, amplified by 32dB and investigated with a commercial bit error rate (BER) detector. In addition the eye-pattern of the soliton transmitter has been observed. In Fig. 3 an example of an eye-diagram for 2nd harmonic modelocking of the 1562nm emission of the laser is shown for a pseudo-random bit sequence (PRBS) of 2^{23}-1. Due to the limitations in the bandwidth of our preamplifier (about 50MHz lower frequency limit) low error rates cannot be achieved for long PRBSs. Therefore we tested the pulse stability using a 1-0-1-0-bit sequence. With this sequence bit error rates of about 10^{-10} have been achieved for gating times in excess of half an hour.

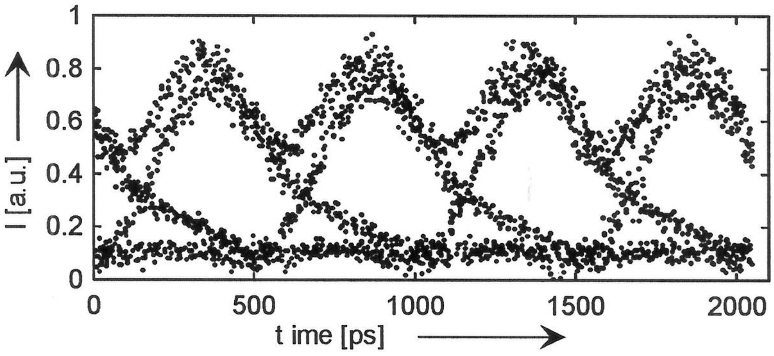

Fig. 3: Eye-diagram of the modelocked soliton transmitter for 2nd harmonic modelocking and 2^{23}-1 PRBS data encoding.

In modelocked laser operation the two main contributions to the laser noise are low frequency relaxation oscillations/spiking and for FM-modelocking the competition of the two interleaved pulse trains, respectively, and high frequency noise due to the competition of supermodes for harmonic modelocking.
To suppress relaxation spiking of the laser during modelocking 9% of the laser output were detected and the detector signal fed to an electronic control circuit which generates and superimposes a correction component to the injection current of the pump laser diode. 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 at the residual relaxation oscillation peak around 450 kHz for 3.5(8.3)dBm of DC-electrical power from the detector (average optical power of the laser). At frequencies above 100 MHz the laser output is almost shot noise limited. Only at frequencies corresponding to integers of the axial mode spacing significant peaks in the electronic spectrum can be observed. In addition to the Fourier

component at the modelocking frequency further components appear at other harmonics of the axial mode frequency spacing as a result of supermode competition.

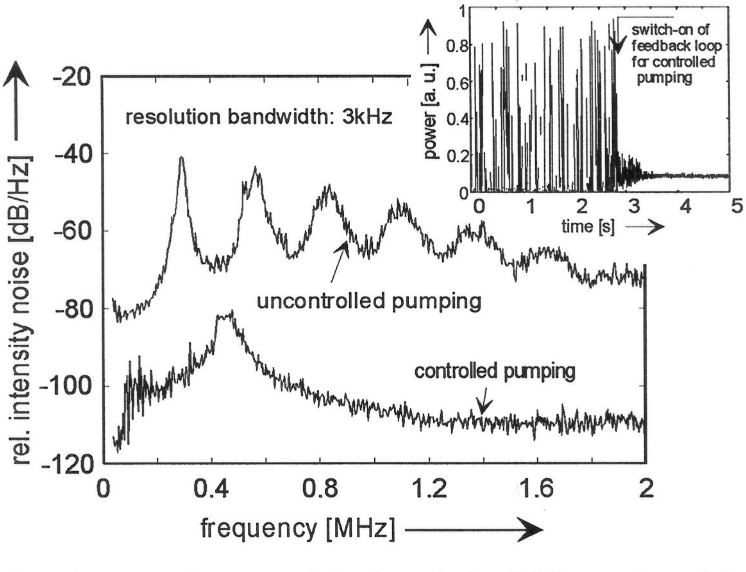

Fig. 4: Relative intensity noise versus frequency of the laser during 5th harmonic modelocking at 1575nm wavelength, π-polarized, for uncontrolled and controlled pumping; inset: transient behaviour of the laser output power upon closing of the feedback loop for controlled pumping.

We are currently investigating low frequency intracavity phase modulation as a means to suppress supermode competition. Up to 8dB suppression of the beat component at the axail mode frequency spacing has already been observed for π-polarized emission at 1575nm wavelength.

Conclusions

We have fabricated and investigated an efficient harmonically modelocked Ti:Er:LiNbO$_3$-soliton source. Its power characteristics, pulse properties, noise and BER after encoding have been studied. By feedback controlled pumping the low frequency RIN of the laser could be reduced by 42dB. Bit error rates down to 10^{-10} have been observed for a 1-0-1-0-bit sequence. Error-free launching of real data (broad Fourier spectrum) for long haul soliton transmission at 10Gbit/s still requires a better suppression of supermode competition.

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