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Integrated InP based modelocked lasers and pulse shapers

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ABSTRACT

In this paper we present recent results obtained in the area of monolithically integrated modelocked semiconductor laser systems using generic InP based integration platform technology operating around 1550nm. Standardized components defined in this technology platform can be used to design and realize short pulse lasers and optical pulse shapers. This makes that these devices can be realized on wafers that can contain many other devices. In the area of short pulse lasers we report design studies based on measured optical amplifier performance data. This work has the ultimate goal to establish a library of widely applicable short pulse laser designs. Such lasers can include components for e.g. wavelength control. An important boundary condition on the laser design is that the laser can be located anywhere on the InP chip. In the area of pulse shaping we report on a 20 channel monolithic pulse shaper capable of phase and amplitude control in each channel. Special attention is given to the calibration of the phase modulator and amplifier settings. Pulse compression and manipulation of pulse generated from modelocked semiconductor lasers is demonstrated using a 40 GHz quantum dash modelocked laser.

Keywords: integrated optics, semiconductor lasers, optical pulse shaping, modelocking

1. INTRODUCTION

Ultra-fast laser systems that generate regular trains of short optical pulses are widely available in many research and development laboratories in academia and industry. These laser systems were initially mostly based on titanium doped sapphire (Ti:S) laser material and Kerr lens modelocking schemes but many of such systems have been or are being replaced by modelocked short pulse fiber lasers and amplifiers and more recently semiconductor disk lasers^{1,2}. This availability of ultra-fast pulses has driven many research areas from basic physics to biological and medical research and to mechanical engineering. Spectacular results have been achieved such as extremely accurate optical frequency combs³, high speed gas spectroscopy⁴ or coherent excitation applications in chemistry and biophotonics⁵. The technological improvements in laser systems now enable application of many of the developed techniques based on ultrafast optical pulses, but the cost of such laser systems is still fairly high. The laser and related optical systems involved can still be bulky and vulnerable. Many the applications are often still in well controlled environments such as medical laboratories where also skilled personnel is available to operate the systems. One issue is that typically not just a modelocked oscillator is required, but also optical and electronic systems. Systems are needed to stabilize the laser operation as for example applications of stabilized frequency combs in telecommunication (clock distribution, multi-wavelength lasers for wavelength-division multiplexed systems) or in high speed gas spectroscopy⁴. In applications in biophotonics and coherent excitation such as multi-photon microscopy or CARS-microscopy⁵ one requires (amplified) optical pulses of a specific intensity and phase at a given time in a specific location of a sample. Therefore not only stability is required but the amplitude and phase of each mode of the comb must be controlled to obtain the optimal optical pulse at the sample. The simplest case is the compensation of dispersion of the optical path between the laser oscillator and the sample. Such systems can be quite bulky, complex and vulnerable. In telecommunication optical pulse shaping can be used to encode information in the intensity and phase information in a frequency comb.

Our aim at the COBRA Research Institute is to use photonic integration to realize integrated semiconductor laser and ultra fast laser systems based on indium-phosphide (InP). Using active-passive integration technology optical amplifiers,

passive waveguide devices and electro-optic phase modulators can be combined on a single monolithic chip⁶. In such technology modelocked laser diodes (MLLD)⁷, special pulse amplifiers⁸ and pulse shaping devices⁹ have been demonstrated. In literature the realization of integrated short pulse lasers and pulse shaper systems for telecommunication application has also been reported^{10,11}. Another advantage is that the devices can be relatively easily combined with fiber based technology devices.

There are a number of issues in the development and realizing of such integrated systems. First is the performance of the MLLDs. Interesting performance has been achieved using quantum well¹² and quantum dot gain materials^{13,14}. The semiconductor modelocked lasers are much more compact and in principle robust, but their overall performance is disappointing. The coherent output bandwidths achieved are much smaller than those of solid state lasers, power levels are quite low and their operating parameter space is typically quite critical. The second issue which slows down development in particular is that fabrication of devices is costly and time consuming. This leads to long feedback cycles in development.

There are currently three highly relevant developments that are helping to bring this area forward. The first is that active-passive integration technology allows for more advanced laser designs to overcome issues in standard two-sections all active MLLD in particular self-phase modulations effects. Active-passive integration allows for a decoupling of amplifier lengths and the resonator length which determines the repetition rate and it allows including intra-cavity devices such as phase modulators or filters. For instance, recent reports in literature show an increase in coherent bandwidth from MLLD using weak intra-cavity spectral filters¹⁵, or control of lasing direction in ring MLLD through a specific lay-out⁷. The second development is the progress in travelling wave modeling tools to describe these more complex laser oscillators. A particularly interesting tool is the FreeTWM open source package¹⁶ which allows for a detailed spectral description of the amplifier and saturable absorber in the laser as well as the effect standing wave pattern in the cavity. A third important development is in integration technology through the introduction of what is named generic photonic integration. In the generic photonic integration approach⁶, a set of components are defined as building blocks. These building blocks provide basic optical functions such as light transmission, phase modulation and amplitude manipulation. A wide range of functionalities may then be realized by combining the standardized building blocks to make complex photonic circuits. By analogy to electronics integration this approach leads to a significant reduction in the effort needed for design and fabrication. The fabrication effort and cost is shared with other designs which can be realized on the same wafer since all designs make use of the same components. This open access fabrication approach gives opportunity to a large group of users to high quality fabrication at a much reduced cost. This generic integration approach is being developed in the framework of the EuroPIC and Paradigm EU FP7 projects as well as within COBRA Research Institute. Currently access for third parties to these platforms is coordinated through the JePPiX organisation¹⁷.

Obviously there are currently some limitations on the optical performance that can be achieved using semiconductor integrated optics and standardized components compared to dedicated technology or solid state laser technology. On one-hand, the standardized integration limits the applications but on the other hand it does allow a much faster development and earlier commercial exploitation of results. Within COBRA the work on modelocked systems is geared towards application of stabilized frequency sources in microwave photonics, non-linear microscopy (in particular CARS microscopy with shaped pulses) and dual modelocked lasers for Fourier Transform Spectroscopy (FTS).

In this paper first the progress on the design modelocked oscillators in the framework of generic integration platforms is described. Designs of linear modelocked laser oscillators with improved stability and output power that can be realized in the technology platforms are studied using the FreeTWM travelling simulation tool¹⁶. This tool requires specific input parameters for amplifiers. These parameters have been extracted for the amplifiers used in the COBRA integration technology platform and are used in a design study to improve linear laser cavity geometries. In the second part of the paper we describe progress in the area of integrated pulse shapers. Experimental results obtained with a 20 channel integrated pulse shaper device realized within the framework of the EuroPIC project are presented.

2. INTEGRATED LINEAR MLLD DESIGN STUDY

Passive mode-locking in semiconductor lasers can be achieved by combining two elements, a semiconductor optical amplifier (SOA) and a saturable absorber (SA) in a cavity which can have a number of different geometries^{18,19}. In order to increase the field intensity profile in the SA, a colliding pulse configuration is commonly applied. For a linear laser in such a configuration the SA is typically placed in the middle of the cavity or next to a high-reflectivity facet. However,

it was recently theoretically predicted²⁰ that placing the SA section close to the output coupler facet with reduced reflectivity (e.g. 20%) leads to a significant increase in output power and a reduction in amplitude and timing jitter. To implement such a design in a photonic integrated circuit with active-passive integration, mirror structures such as a distributed Bragg reflector or an MMI reflector²¹ should be used. Such structures have however a finite length. The presence of such additional passive sections in the resonator can have a significant influence on the interaction of the pulse with itself in the absorber.

In the work presented here, the performance of Fabry-Perot modelocked lasers with the SA placed close to the output coupler of a finite length is studied. For this study we use the travelling wave simulation software package FreeTWM¹⁶ that was used as in²⁰. Experimentally obtained gain characteristics from quantum well optical amplifiers were used in the input parameters for the simulations.

2.1 Amplifier gain parameterization

The measurements of the gain spectra were performed on quantum well InGaAsP/InP SOAs with four quantum wells in the layer stack for a range of injection currents. This is a standard four quantum well gain layer stack in the COBRA technology platform. The measurement method is based on the analysis of amplified spontaneous emission (ASE) spectra from different lengths of SOA^{22,23}. Using this method the gain spectra can be measured over a wide range of injection currents. The ASE spectra were measured for four different lengths of SOA (100 – 200 – 400 and 800µm) operated at the same constant current density and temperature of 18° C. This series of amplifiers of different lengths was positioned on a single chip that was fabricated using active-passive integration technology.

Fig.1. Experimentally obtained gain spectra (blue curve) for injected 1880 A/cm², 2000 A/cm², 2200 A/cm², 2400 A/cm², 3000 A/cm², 4000 A/cm², 5000 A/cm², 6000 A/cm², 7000 A/cm², 8000 A/cm², and fitted curves (red).

The blue curves in Figure 1 are the measured gain spectra for the different current densities. The red curves in Figure 1 correspond to the fitting results which were obtained using the formula²⁴:

$$G(\omega, N) = \chi_0 \left[\arctan\left(\frac{\omega - \omega_0}{\gamma}\right) - 2 \arctan\left(\left(\frac{\omega - \omega_0}{\gamma}\right) - \frac{N}{N_0}\right) - \frac{\pi}{2} \right] + losses$$

where χ_0 is the maximum saturated gain, ω is the frequency, N is the carrier density, N_0 is the carrier density at the band gap frequency ω_0 , γ is width of optical transition. The parameter values for ω_0 , N_0 , γ and χ_0 extracted from the fitting are $(1.855 \pm 0.02) \times 10^{14}$ Hz, $(3.8 \pm 0.2) \times 10^{23}$ m⁻³, $(0.06 \pm 0.015) \times 10^{14}$ Hz and 80 ± 20 cm⁻¹ respectively. For the losses a value of 9.5 ± 2 cm⁻¹ was found. These values were used in the simulation of Fabry-Perot modelocked laser as characteristics of gain medium.

2.2 Fabry-Pérot MLLD simulations – optimizing the position of the absorber

Simulations of a linear passively modelocked laser with a repetition rate of 40 GHz were performed using the FreeTWM (Travelling Wave Model) software¹⁶ and the measured parameters reported above. The length of the simulated device is 1.04 mm and the refractive group index is taken to be 3.6. The laser cavity has an output coupler (OC) mirror with 20%

reflectivity. Next to the OC are a short passive section and a SA. Then there is a SOA and a high reflectance (HR) facet at the side of the SOA with $R = 80\%$. The recovery time of the SA was taken to be 10ps.

A first series of simulations was performed to study of the influence of the absorber length on the mode-locking regime. This has shown that a stable regime of mode-locking can be obtained for a SA length around $25\text{ }\mu\text{m}$. For the SA with a length $\sim 40\text{ }\mu\text{m}$ and more, passive Q-switched mode-locked operation is observed. For shorter SA sections a second (satellite) pulse can be observed in the pulse train.

Then a series of simulations was done to investigate the maximum length of passive section between the OC and SA that could be used before the mode-locking was destabilized. In this series the injected current was set at 19 times the amplifier transparency current J_{tr} . Simulations were carried out for $50\text{ }\mu\text{m}$ to $300\text{ }\mu\text{m}$ length of passive section between the reflector and a $25\text{ }\mu\text{m}$ long SA. The results show that the power and stability of the pulses improves with decreasing of length of passive section as one might expect. It turns out that good mode-locked operation with stable pulses can still be obtained for lengths of the passive section between the OC and the SA of $100\text{ }\mu\text{m}$. This distance corresponds to approximately 1.2 ps. The simulations thus show that the effective reflection point of the output coupler mirror structure (e.g. a short DBR or MMI reflector) must be realized within $100\text{ }\mu\text{m}$ from the SA.

The third series of simulations presented here were performed to see if the advantage of the positioning of the SA near the OC remains with the passive section. Simulations were done for a range of SOA currents for two configurations. In configuration 1 (result Set 1) the SA is positioned next to the short passive section and the OC. In configuration 2 (result Set 2) the SA is positioned next to the HR mirror. All other parameters are kept the same. Some of the key results are presented in Figure 2.

Fig.2. Simulation results of the configurations 1 and 2 (Set 1 and Set 2) of the 40GHz passively modelocked laser for three different current values, $7.5 \cdot J_{tr}$, $12.5 \cdot J_{tr}$ and $20.5 \cdot J_{tr}$. The top row figures show the output intensity in arbitrary units as a function of time for the full simulation. The middle row shows a small section from the time traces in the first row to make the individual pulses in the pulse train are visible. In the third row the optical spectra of the laser output in the last 10ns of the simulation are presented. The frequency scale gives the offset frequency from the carrier frequency in the simulation of $1.855 \cdot 10^{14}\text{Hz}$.

Figure 2 shows simulation results for three different current values, $7.5 \cdot J_{tr}$, $12.5 \cdot J_{tr}$ and $20.5 \cdot J_{tr}$. The top row figures show the output intensity in arbitrary units as a function of time for the full simulation. The second row shows a detail from the time traces in the first row where individual pulses in the pulse train are visible. In the third row the optical spectra of the laser output in the last 10ns of the simulation are presented. The frequency scale gives the offset frequency from the carrier frequency in the simulation of $1.855 \cdot 10^{14}\text{Hz}$ which is the value of ω_0 determined in the gain measurements.

Both laser configurations start modelocking not far above the lasing threshold is just below $4 \cdot J_{tr}$. Configuration 2 (SA next to HR) shows stable modelocking at a current level of up to approximately $9 \cdot J_{tr}$. Above this level the laser starts to

emit satellite pulses which grow, then become the main pulse and then become weaker again as another satellite pulse grows. This is the origin of the variation in the envelope of the time traces a) at $12.5 \cdot J_{tr}$ and $20.5 \cdot J_{tr}$. Configuration 1 (SA close to OC) shows stable modelocking up to $15 \cdot J_{tr}$. Above these current levels there is a more gradual transition to a regime with variations in pulse energy and width at relatively low frequencies (below the relaxation oscillation frequency actually). But the laser keeps emitting a train of clearly defined pulses. Due to the variation in pulse energy however there is a significant variation in roundtrip time which are linked in passive modelocking with a slowly recovering saturable absorber. The simulation results $20.5 \cdot J_{tr}$ show both laser configurations operating outside a good modelocking regime one can clearly see the difference in behavior of the two systems. The multiple pulse instabilities in configuration 2 may be suppressed more by using a somewhat longer absorber or higher reverse bias voltage (reduced carrier lifetime) but this will reduce the laser output power and the laser will show passive Q-switch like behavior. Our results do confirm that configuration 1 is more favorable.

Using the results of such simulations we are currently designing test devices that are to be realized in generic integration platforms. Combining the results from the theory and the device measurements we plan to develop a library of useful MLLD that can be combined with other optical devices on the same chip, such as the optical pulse shaper presented below. Such a combination allows for a fully integrated pulse source with configurable pulse shape and or phase profile which can be used to pre-compensate dispersion. Such a device can then be fabricated reliably in a qualified process on the short term.

3. INTEGRATED OPTICAL PULSE SHAPING

3.1 Design and characterization

The pulse shaper device is designed upon the Fourier transform pulse shaping approach²⁵. In the Fourier transform technique, a spectrally dispersive element is used to decompose the incident optical pulse into its constituent spectral components. The phase and amplitude of the spectral components are then controlled by a spatial mask which is patterned according to the desired synthesized pulse shape. An optical grating is then used to combine the spectral components to form the shaped pulse.

The integrated device operates in the reflection mode. The light from the optical pulse source, i.e. the optical emission of an MLLD, is injected into the pulse shaper chip via an anti-reflection (AR) coated facet. The pulsed signal passes through an AWG which decomposes the light into its spectral components. Spectral components pass through electro-optic (EO) phase modulators (PMs) and SOAs and are then reflected back from a facet with a high-reflection (HR) coating. The PMs and SOAs are used to manipulate the spectral phase and amplitude of the components. The spectral components are then recombined in the AWG and return through the input/output (I/O) waveguide. The two directions are separated by a circulator outside the chip. Fig. 3(a) demonstrates the schematic diagram of the device operation. A microscope image of the realized chip is shown in Fig. 3(b). The total size of the device is $6 \times 6 \text{ mm}^2$.

Fig. 3. (a) Schematic diagram of the pulse shaper which shows the operation principle in the reflection mode. (b) Microscope image of the realized pulse shaper. The total size of the device is $6 \times 6 \text{ mm}^2$. AR: anti-reflection, HR: high-reflection.

In the reflective design, a single AWG is required to de-/multiplex the optical pulse components. Furthermore, the signal in each AWG channel passes through the optical elements twice. Therefore, it is more efficient, compact and tolerant to the fabrication process, and hence, attractive for realization in a generic integration platform. An important issue in the

performance of a pulse shaper in reflective mode is the effect of unwanted reflections from on-chip components and the facet. To minimize the back reflections in the current device, the I/O waveguides are angled and the I/O facet is AR-coated. In case of the device under test, the total unwanted reflection level is measured to be at least 21 dB lower than the signal. Furthermore, an AR-coated lensed fiber tip is used to inject the pulsed signal to the chip and collect the return signal.

The current design includes a total number of 20 SOAs as well as 20 PMs. Extra sections of waveguides are included in each AWG channel to compensate for the path length differences. Total on-chip loss (double-pass, excluding gain of SOAs) is ~ 20 dB. The SOAs are $750\text{ }\mu\text{m}$ long and biased up to 40 mA to provide around 7 dB double-pass optical gain and low amplified spontaneous emission (ASE) power levels. The 7 dB optical gain is lower than the expected value possibly due to higher background losses in the SOA structure. A higher optical gain is indeed beneficial to (ideally fully) compensate for the device losses. For the pulse shaping application, the possibility to control the relative gain of SOAs in each device channel is important. In this way, the relative amplitude of spectral lines may be adjusted according to the specified pulse shape by controlling the relative gain of SOAs. If an SOA is biased below transparency, extra losses are induced due to absorption. A frequency component of the pulse may be effectively eliminated by reverse-biasing the SOA.

The AWG has a cyclic design with 20 channels at 50 GHz spacing. The free spectral range is 8 nm. The AWG transmission spectrum is flat within 3 dB and the insertion loss is approximately 5 dB. In order to characterize the spectral transmission through the AWG, the SOA in channel 9 was biased at $I_{\text{SOA}}=30\text{ mA}$ and the generated ASE power is measured at the I/O waveguides. Fig. 4 shows the spectra of the fiber-coupled optical power and indicates the shape of AWG channels. The full width at half maximum (FWHM) spectral width of AWG channels is designed to be 50 GHz whereas measurements show a FWHM of $\sim 65\text{ GHz}$ which is attributed to phase errors in the AWG arms.

Fig. 4. Fiber-coupled optical spectral power. SOA 9 is biased at $I_{\text{SOA}}=30\text{ mA}$ and the ASE power is recorded at I/O waveguides. AWG has a cyclic design and the free spectral range is $\text{FSR}=8\text{ nm}$.

Fig. 5. Recorded sensor temperature vs the number of SOAs biased at $I_{\text{SOA}}=30\text{ mA}$ (blue) and $I_{\text{SOA}}=40\text{ mA}$ (pink).

The chip is mounted on a subcarrier which provides wire-bond pads for connection to the control instruments via a printed circuit board. The subcarrier is then mounted on a water-cooled copper block which is used to stabilize the

operating temperature. A thermistor is used to monitor the temperature. The actual device temperature depends on power dissipation in SOA sections as well. When all the SOAs on chip are biased at $I_{SOA}=30\text{--}40\text{mA}$, the sensor indicates about $0.5\text{--}0.7^\circ\text{C}$ increase in temperature. This corresponds to a temperature change of less than $0.01^\circ\text{C}/10\text{mA}$. The recorded temperature vs the number of biased SOAs is given in Fig. 5. A 0.5°C increase in the temperature shifts the AWG spectrum to longer wavelengths by approximately 8 GHz. Therefore, the effect of small changes in I_{SOA} on operating conditions of the device is negligible. The results presented here are obtained at $T=12^\circ\text{C}$.

The PMs on the pulse shaper chip are 1mm long. They are operated by reverse bias voltage and are used to apply certain phase masks on the spectral components of the input pulse. To increase the phase shifting efficiency, the PMs are oriented parallel to the wafer major flat. In this direction the linear EO effect adds to the quantum-confined Stark effect. The dark current is measured to be 2.5 nA to 4 nA for reverse bias $V_{PM}=0$ to $V_{PM}=-5$ V. When the corresponding SOA in the channel is biased at $I_{SOA}=30$ mA, the current through the PM is $I_{PM}=2$ μA at $V_{PM}=0$ V and increases to $I_{PM}=21$ μA at $V_{PM}=-5$ V. The increased reverse current is caused by higher light absorption in presence of the external electric field. The amount of excess loss induced by the reverse-biased PMs is lower than 1 dB for $|V_{PM}|<4$ V.

3.2 Phase modulator calibration

It is possible to characterize the phase tuning performance of the PMs on chip. The neighboring channels of the AWG have 3 dB overlap at FWHM. Therefore, if an external light signal with a wavelength in between the central wavelengths of two adjacent channels is injected to the chip, the optical power is effectively split between the two channels. In each arm, the light will pass through the PM and SOA, reflect back on the HR-coated facet and then recombine by the AWG to return to the input waveguide. This structure effectively forms a Michelson interferometer which is used to characterize the phase shifters. Changing the bias voltage on a phase shifter in one arm induces a phase difference and thus changes the return optical power due to interference. Typical results are given in Fig. 6(a) which shows the interference patterns for the AWG channels number 8 and 9. These curves are then analyzed to obtain the phase tuning curves, such as those shown in Fig. 6(b). The required voltage for a 2π phase change (double-pass) is about 3.6-4 V for a range of $\lambda\sim 1535\text{--}1550$ nm.

Fig. 6. (a) Typical interference patterns which are used to characterize the phase tuning performance of the phase modulators at $\lambda=1536.7$ nm (blue cross), $\lambda=1543.8$ nm (green dot) and $\lambda=1551.7$ nm (red triangle). (b) Induced phase shift vs reverse bias voltage for different wavelengths.

3.3 Demonstration of Chirp Compensation

Spectral phase control of optical pulses is often required to generate short pulses. An important application of the pulse shaper chip is spectral chirp/dispersion (pre-) compensation. To demonstrate the functionality of the device under test, we have used a 40 GHz passively MLLD which generates highly chirped optical pulses. Optical pulses are characterized in time-domain using the stepped heterodyne technique²⁶. This technique is a linear measurement method which is particularly useful in spectral and temporal phase characterization of passively MLLD, where no external electronic clock is available.

The ML laser is a single-section, 1mm-long, quantum dash Fabry-Pérot device with no SA section²⁷. It is operated at 375 mA (with no direct or external modulating signal applied) and at $T=18^\circ\text{C}$. The total power at the output of the laser is 3 dBm. We have first excluded the pulse shaper chip from the setup to characterize the optical pulse which is

generated by the MLLD and passed through our measurement setup. In order to reliably measure the signal with the real-time oscilloscope, Erbium-doped fiber amplifiers (EDFAs) are used to boost the signal level. Oscilloscope traces are then analyzed to characterize the pulse shape. The result is shown in Fig.7(a) and it is clear that the pulse has a chirp profile that is not linear, mostly attributed to the material dispersion²⁸. The pulse has FWHM of 3 ps with an asymmetric temporal shape which spans over 6.6ps at 6dB below the top of peak. It must be mentioned that the laser operates around $\lambda=1529$ nm and hence a part of the optical spectrum which falls outside the EDFA gain bandwidth is suppressed. Therefore, the results are effectively obtained for 4nm spectral bandwidth.

Next, the optical pulse is characterized after passing through the pulse shaper. In principle, the required control signals, i.e. values of bias voltage on PMs and current of SOAs, can be calculated by considering the spectral phase and amplitude of the incident pulse and the shape of the desired pulse to synthesize, which is in this case an ideal transform-limited optical pulse. Tuning the control signals on PMs affects the spectral phase profile and changes the pulse shape. We have found and optimized the phase settings by monitoring the autocorrelation signal to maximize the peak power and reduce the time duration. The SOA sections in all the operating channels are biased at $I_{SOA}=40$ mA. Fig.7(b) shows the temporal signal and chirp of the output pulse. It is clear that the chirp profile over the duration of the optical pulse is nearly flat and the trailing edge is significantly suppressed. The FWHM of the pulse is 2.17 ps and the width at 6 dB below the top of the peak has reduced to 2.9 ps.

Functionality of the device is further verified by investigating the optical pulses in the frequency domain. This provides a clear insight on the Fourier transform shaping capability of the device. The spectral phase is measured using the stepped heterodyne technique. In order to clearly visualize the spectral lines, i.e. the frequency components, a high resolution (20 MHz) optical spectrum analyzer is used to record the power spectrum as reference.

Fig. 7(c) shows the measured spectral power (open circles, normalized and offset by -10 dB for better visibility) and phase (filled squares) of the optical pulse generated by the ML source and passed through the measurement setup, excluding the pulse shaper. The high resolution power spectrum (solid line) is given and indicates the optical lines which are separated by 40 GHz, i.e. the ML repetition frequency.

Fig. 7. Normalized temporal amplitude (left axis) and chirp (right axis) of the optical pulse (a) generated by the quantum dash laser and passed through the measurement setup only, and (b) with the pulse shaper chip included for chirp compensation. Spectral power (left axis, dBm) and phase (right axis, radians) of the optical pulse (c) generated by the quantum dash laser and passed through the measurement setup only, and (d) with the pulse shaper chip included. High resolution spectra (solid line) show the laser modes.

Fig. 7(d) corresponds to the optical pulse when the pulse shaper chip is included in the measurement setup. The spectral phase profile is nearly flat for 11 optical lines at the higher frequency side of the spectrum. However, it is clear that the

chirp is not fully compensated and the power spectrum is not flat due to the mismatch between the repetition frequency of the source and the channel spacing of the device. In Fig. 7(d), the spectral power measured with the stepped heterodyne technique (open circles) shows a good agreement with the recorded power spectrum measured with the high resolution optical spectrum analyzer (solid line). This verifies the reliability of the measurement method and indicates that the pulse train from the laser is sufficiently stable.

4. CONCLUSION

In this paper we have presented work on components for pulsed lasers systems. This consists of work to obtain a library of modelocked laser oscillators and devices to manipulate optical pulses which is integrated together in an InP photonic integration technology platforms. Specifically we have presented theoretical results on optimizing the position of the SA in a linear MLLD while staying within the technical constraints of the technology platform. In the area of pulse shaping we have demonstrated a monolithically integrated pulse shaper that contains standardized components such as electro-optic phase modulators and semiconductor amplifiers in the wavelength dispersed arms. A reduction of the pulse width to 2.9 ps and a suppression of the chirp for almost of the lasing mode were achieved by our 6x6 mm² pulse shaper.

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