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ULTRASHORT, HIGH POWER, AND ULTRALOW NOISE MODE-LOCKED OPTICAL PULSE GENERATION USING QUANTUM-DOT SEMICONDUCTOR LASERS

by

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> A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Optics and Photonics at the University of Central Florida Orlando, Florida

> > Fall Term 2006

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ABSTRACT

This dissertation explores various aspects and potential of optical pulse generation based on active, passive, and hybrid mode-locked quantum dot semiconductor lasers with target applications such as optical interconnect and high speed signal processing.

Design guidelines are developed for the single mode operation with suppressed reflection from waveguide discontinuities. The device fabrication procedure is explained, followed by characteristics of FP laser, SOA, and monolithic two-section devices.

Short pulse generation from an external cavity mode-locked QD two-section diode laser is studied. High quality, sub-picosecond (960 fs), high peak power (1.2 W) pulse trains are obtained. The sign and magnitude of pulse chirp were measured for the first time. The role of the self-phase modulation and the linewidth enhancement factor in QD mode-locked lasers is addressed.

The noise performance of two-section mode-locked lasers and a SOA-based ring laser was investigated. Significant reduction of the timing jitter under hybrid mode-locked operation was achieved owing to more than one order of magnitude reduction of the linewidth in QD gain media. Ultralow phase noise performance (integrated timing jitter of a few fs at a 10 GHz repetition rate) was demonstrated from an actively mode-locked unidirectional ring laser. These results show that quantum dot mode-locked lasers are strong competitors to conventional semiconductor lasers in noise performance.

Finally we demonstrated an opto-electronic oscillator (OEO) and coupled opto-electronic oscillators (COEO) which have the potential for both high purity microwave and low noise optical pulse generation. The phase noise of the COEO is measured by the photonic delay line

iii

frequency discriminator method. Based on this study we discuss the prospects of the COEO as a low noise optical pulse source.

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TABLE OF CONTENTS

LIST OF FIGURES	ix
LIST OF TABLES	xvi
LIST OF ACRONYMS/ABBREVIATIONS	xvii
CHAPTER 1: INTRODUCTION	1
1.1 Motivations	1
1.2 Dissertation Statement and Outline	4
REFERENCES	6
CHAPTER 2: REVIEW OF SEMICONDUCTOR LASER MODE-LOCKING	8
2.1 Quantum Dot Material	8
2.2 Linewidth Enhancement Factor and Linewidth in Semiconductor Lasers	9
2.3 Semiconductor Optical Amplifier (SOA)	12
2.4 Mode-Locking of Semiconductor Lasers	15
2.4.1 Active Mode Locking	15
2.4.2 Passive Mode Locking	15
2.4.3 Hybrid Mode Locking	
2.4.4 Description of Mode Locking	
REFERENCES	
CHAPTER 3: DEVICE DESIGN, FABRICATION, AND CHARACTERIZATION	
3.1 Structure of the QD Wafer	
3.2 Waveguide Analysis and Device Design	
3.2.1 Waveguide Analysis for Single Transverse Mode Operation	

3.2.2 Ridge Waveguide (RW) Fabry-Perot Laser Diodes	26
3.2.3 Semiconductor Optical Amplifier (SOA)	27
3.2.4 Monolithic Mode-Locked Laser (MML) Diode	33
3.3 Device Fabrication Procedure	37
3.4 Device Characteristics	49
3.4.1 Characteristics of FP Laser Diodes	49
3.4.2 Characteristics of QD-SOA	55
3.4.3 Characteristics of MML Diodes- Monolithic Device	57
REFERENCES	59
CHAPTER 4: ULTRASHORT, HIGH PEAK POWER PULSE GENERATION FROM A	
MONOLITHIC MODE-LOCKED LASER	63
4.1 Introduction	63
4.2 Laser Setup and Results	64
4.3 Grating Coupled External Cavity	71
4.4 Discussions	73
REFERENCES	76
CHAPTER 5: ULTRALOW NOISE OF QUANTUM-DOT MODE-LOCKED LASERS	79
5.1 Introduction	79
5.2 Noise of Mode-Locked Semiconductor Lasers	80
5.2.1 Noise of Mode-Locked Lasers	80
5.2.2 Harmonic Mode Locking and Supermode Noise	83
5.2.3 Absolute and Residual Phase Noise Measurement	84
5.3 Timing Jitter of QD Monolithic Mode-Locked Lasers	86

	5.4 Modal RIN of a QD Mode-Locked Laser	91
	5.5 Active Mode Locking of a Ring Laser	96
	5.5.1 Setup and Characteristics of the Laser	96
	5.5.2 Noise Measurements	. 100
	5.6 Effects of Chip Modes on Active Mode Locking Performance	. 106
	REFERENCES	. 111
С	HAPTER 6: QUANTUM-DOT LASER BASED OPTO-ELECTRONIC-OSCILLATOR	. 115
	6.1 Introduction	. 115
	6.2 Opto-Electronic Oscillator (OEO) as a Ultralow Phase Noise Microwave Signal Sour	rce
		. 116
	6.3 Coupled Opto-Electronic Oscillator (COEO)	119
	6.4 Absolute Phase Noise Measurement by sing Photonic Delay Line Method	. 121
	6.5 Regenerative Mode Locking Based on Passive Mode-Locked Two-section Devices	. 125
	REFERENCES	. 127
С	HAPTER 7: SUMMARY AND FUTURE WORKS	129
	7.1 Summary	129
	7.2 High Power QD lasers	. 130
	7.3 Dispersion Managed Mode-Locked Laser using Waveguide Saturable Absorbers	. 133
	7.4 Tunnel Injection Laser	. 134
	7.5 Conclusion	. 135
	REFERENCES	136

LIST OF FIGURES

Fig.2 - 1: Shape of active region and density of states versus energy level; Bulk, Quantum well,
Quantum wire, and Quantum dot. The crossed regions denote filled states
Fig.2 - 2: A simple model of growing ASE power in an optical amplifier
Fig.2 - 3: Intensity transmission curve of a saturable absorber
Fig.2 - 4: Monolithic two-section single chip device
Fig.3 - 1: Index difference versus etching depth of waveguide
Fig.3 - 2: Structure of a RW structure, (a) SiN, (b) BCB as an insulating layer
Fig.3 - 3: SOA with tilted waveguide
Fig.3 - 4: Residual reflectivity of the fundamental mode ($\Delta n=0.005$) for different waveguide
width
Fig.3 - 5: Residual reflectivity versus tilt angles, determined by the Kaminow-Eisenstein method.
Fig.3 - 6: Tapered SOA near facets, proposed in [14]
Fig.3 - 7: BPM simulation with different transient length, (a) L=0 μ m; corresponds to the abrupt
change of the waveguide width, (b) L=40 μ m; slow change of the waveguide width
Fig.3 - 8: Power conversion efficiency for different taper lengths, (a) $0^{th} - 0^{th}$ mode, (b) $0^{th} - 2^{nd}$
mode
Fig.3 - 9: Design of the waveguide in the first generation MML diode
Fig.3 - 10: (a) Optical spectrum which shows the detrimental effect of the reflection at the gap,
(b) zoom-in

Fig.3 - 11: Another solution to reduce the back-reflection at the gap. The top contact layer is	
etched separately with the ridge forming process	36
Fig.3 - 12: Final design of the waveguides of two section devices.	37
Fig.3 - 13: Wafer orientation. US standard and EJ standard.	39
Fig.3 - 14: Scanning electron micrograph (SEM) image of a waveguide formed in the wet-	
etching step. The etchant is H ₃ PO ₄ :H ₂ O ₂ :H ₂ O=1:2:50.	42
Fig.3 - 15: Scanning electron micrograph (SEM) image of a waveguide formed in the wet-	
etching step. The etchant is H_3PO_4 : H_2O_2 :Methanol: $H_2O = 0.75$:1:1:3.	43
Fig.3 - 16: Metal liftoff process.	44
Fig.3 - 17: Reflectance of single-layer SiO _x N _y AR coating on GaAs-wafer with target	
wavelength of 1550 nm, measured with the Cary spectrophotometer	47
Fig.3 - 18: A device picture of a ready-to-mount monolithic mode-locked laser device	48
Fig.3 - 19: (a) Light output vs currents (LI), and (b) voltage vs currents (VI) for a 1 mm FP LI	D.
	49
Fig.3 - 20: Inverse of the slope efficiency as a function of device length, and fit to Eq. (3-1)	51
Fig.3 - 21: (a) Optical spectrum, (b) Beam profile, of a 1 mm long FP LD.	51
Fig.3 - 22: (a) ASE optical spectrum of a 2 mm QD FP laser didoe, (b) group index, ng	52
Fig.3 - 23: (a) Group index, and (b) GVD of a 2 mm QD FP laser diode at 1267 nm waveleng	th.
	53
Fig.3 - 24: (a) Optical spectrums with different injection currents, (b) zoom-in	54
Fig.3 - 25: (a) Wavelength shift and net gain change versus current, and (b) linewidth	
enhancement factor versus current	55
Fig.3 - 26: (a) LI, and (b) optical spectrum of a QD SOA	56

Fig.3 - 27: Optical spectrum of QD SOA versus injection current
Fig.3 - 28: Optical gain versus output power
Fig.3 - 29: (a) LI for different reverse bias currents, (b) LI showing the hysterisys behavior 58
Fig.4 - 1: Experimental setup. I - Isolator; OC – Output Coupler (R=70%); QD-ECML –
Quantum Dot External Cavity Mode-Locked Laser; QD-SOA – Quantum Dot
Semiconductor Optical Amplifier
Fig.4 - 2: Spectrum of passive mode-locked pulses. DC=118 mA, Reverse bias voltage=-5V. (a)
Optical spectrum, (b) RF spectrum
Fig.4 - 3: RF spectrum of PML. (a) 100 mA, -4 V (b) 100 mA, -5.6 V
Fig.4 - 4: Zoom-in RF spectrum of (a) passive mode-locked, (b) hybrid mode-locked pulse train.
RBW (resolution bandwidth)
Fig.4 - 5: Sampling trace of optical pulse trains
Fig.4 - 6: (a) Normalized autocorrelation trace with different reverse bias voltage, (b) FWHM of
autocorrelation signal versus reverse bias voltage on absorber section at DC=118mA 69
Fig.4 - 7 Schematic of dual grating dispersion compensator in the 4-f system
Fig.4 - 8: Compressed pulse width versus the offset location of the second grating
Fig.4 - 9: Autocorrelation signal of the compressed pulses
Fig.4 - 10: A grating coupled external cavity monolithic mode-locked laser
Fig.4 - 11: Optical spectrum of grating-coupled passive mode-locking, showing the wavelength
tunability72
Fig.4 - 12: The chirp of pulses as a function of (a) driving currents and (b) reverse bias voltages.
74

Fig.5 - 1: Amplitude fluctuation and timing jitter of mode-locked pulse trains	30
Fig.5 - 2: Phase detector method to measure the noise of a device under test (DUT)	34
Fig.5 - 3: Absolute Phase Noise of E8247C synthesizer at 10.24 GHz. The synthesizer model ha	as
been extensively used as a RF driving source for this study	35
Fig.5 - 4: Residual phase noise measurement	36
Fig.5 - 5: Schematic of the setup. MLL: model-locked laser, M: mirror, OI: optical isolator 8	37
Fig.5 - 6: (a) Optical spectrum, the inset shows the close-in optical spectrum showing combs	
with 10 GHz spacing, (b) autocorrelation	37
Fig.5 - 7: Residual phase noise of 10 GHz hybrid mode-locked two-section mode-locked laser.	
	38
Fig.5 - 8: delayed self-homodyne setup to measure to the average linewidth spectral combs of	
MLL, PC (polarization controller), OI (Optical isolator), DSO (Digital sampling	
oscilloscope), PD (photodetector)	39
Fig.5 - 9: Sampling scope trace (a) before pulse overlap, (b) after overlap) 0
Fig.5 - 10: RF spectrum of the photodetector current) 1
Fig.5 - 11: Setup of a grating coupled external cavity based on a two-section device. QD SOA is	S
used to amplify the output) 2
Fig.5 - 12: (a) Optical spectrum, and (b) autocorrelation) 3
Fig.5 - 13: Grating-based optical filter. D – detector, OSC – oscilloscope, OSA – optical	
spectrum analyzer, RFSA – RF spectrum analyzer) 4
Fig.5 - 14: Filtered optical spectrum) 4
Fig.5 - 15: Measured modal-RIN) 5
Fig.5 - 16: Linear optical cavity) 6

Fig.5 - 17: Optical spectrum at (a) $I/I_{th}=1.02$ (54 mA), and (b) $I/I_{th}=1.22$ (65mA)	97
Fig.5 - 18: Optical spectrum at 200 mA (I/I_{th} =3.6) in a ring laser cavity	97
Fig.5 - 19: Schematic of the unidirectional QD ring laser, QD-SOA, I: isolator, AM: Amplitud	e
modulator, OC: 20% output coupler, PC: Polarization controller	98
Fig.5 - 20: Light output of the oscillator versus injection currents	99
Fig.5 - 21: Optical spectrum (a) logarithmic, (b) linear scale	99
Fig.5 - 22: (a) mode-locked pulse trains, (b) RF spectrum	100
Fig.5 - 23: Supermode level versus RF frequency detuning 1	101
Fig.5 - 24: Optical and RF spectrum versus RF frequency detuning 1	102
Fig.5 - 25: Supermode noise level versus DC currents 1	103
Fig.5 - 26: Residual phase noise and integrated timing jitter 1	104
Fig.5 - 27: AM noise of actively modelocked ring laser at 12.7 GHz 1	105
Fig.5 - 28: Ring laser with an intracavity Fabry-Pérot (FP) etalon to suppress supermode noise) .
	106
Fig.5 - 29: Harmonic modelocked linear cavity 1	107
Fig.5 - 30: RF spectrum of mode-locked pulses of the linear cavity laser (a) without mirrors, (b)
with mirrors1	107
Fig.5 - 31: Ring laser cavity with facets as partial mirrors 1	108
Fig.5 - 32: Phase noise of the ring laser, waveguide angle 2 degree, (a) 88 mA, (b) 110 mA 1	108
Fig.5 - 33: Phase noise of the ring laser, waveguide angle 3 degree, (a) 110 mA, (b) 150 mA. 1	109
Fig.5 - 34: (a) Supermode phase noise level of the ring laser as a function of DC current for	
devices with different waveguide angles, (b) DC current is normalized to the threshold	
current of the Ring Cavity 1	109

Fig.6 - 1: Schematic of OEO
Fig.6 - 2: Oscillation modes of the OEO loop. The τ_d is the delay time of the loop
Fig.6 - 3: OEO based on a tunable laser source. The center frequency is 640 MHz. Red lines
represent light path, black lines prepresent electrical signals
Fig.6 - 4: Sinusoidal RF tone generated from the OEO. The length of additional fiber is (a) no
additional fiber, (b) 100 m, and (c) 1 km. The span is 50 kHz in all cases 118
Fig.6 - 5: Multimode oscillation at higher loop gain, EDFA pumping current of (a) 180 mA, (b)
200 mA
Fig.6 - 6: Setup of COEO
Fig.6 - 7: RF/microwave tone without additional fiber in the RF/microwave loop with span of (a)
50 MHz, and (b) 20 kHz
Fig.6 - 8: Delay line frequency discriminator method
Fig.6 - 9: Photonic delay line method for measurement of the absolute phase noise using a low
loss fiber delay
Fig.6 - 10: Setup for the absolute phase noise measurement using the frequency discriminator
method
Fig.6 - 11: Absolute phase noise of the COEO and comparison with HP83712B synthesizer 123
Fig.6 - 12: Typical phase noise behavior of RF amplifiers; it consists of flicker noise (\sim 1/f) and
white noise. The data is the phase noise of a Miteq amplifier at10 GHz
Fig.6 - 13: COEO using the monolithic mode-locked laser
Fig.6 - 14: RF spectrum of pulse trains. dash-dot-dash, PML, dash-dash COEO, and straight line,
hybrid ML. Both COEO and HML greatly reduce the noise level. The modulation period of
~300 kHz corresponds to the mode spacing of the OEO loop, 500 m fiber delay 126

Fig.7 - 1: Schematic of tapered amplifier, (a) straight preamplifier requires very good AR co	oating
to prevent lasing, (b) preamplifier section is curved	131
Fig.7 - 2: BPM simulation of a tapered amplifier	132
Fig.7 - 3: Waveguide structure of deep-etched SOAs and two-section devices for high outp	ut
power	132
Fig.7 - 4: Schematic of a dispersion managed mode-locked laser using a waveguide saturable	
absorber and gain separately	134

LIST OF TABLES

Table 1: QD laser wafer structure. 2	23
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LIST OF ACRONYMS/ABBREVIATIONS

AM	Amplitude Modulation
AML	Active Mode-Locked
AR	Anti-Reflection
ASE	Amplified Spontaneous Emission
BPF	Band Pass Filter
BW	Bandwidth
CDMA	Code Division Multiple Access
COEO	Coupled Opto-Electronic Oscillator
DFB	Distributed Feedback Laser
DH	Double-Hetero
DOS	Density Of States
DUT	Device Under Test
ECML	External Cavity Mode-Locked Laser
EDFA	Erbium-Doped Fiber Amplifier
GVD	Group Velocity Dispersion
HML	Hybrid Mode Locking
LEF	Linewidth Enhancement Factor
LI	Light Output Versus Currents
ML	Mode-Locking
MLL	Mode-Locked Laser
MML	Monolithic Mode-Locked Laser

NF	Noise Figure
MOPA	Master-
OEO	Opto-Electronic Oscillator
PECVD	Plasma Enhanced Chemical Vapor Deposition
PM	Phase Modulation
PML	Passive Mode Locking
PR	Photoresist
RF	Radio-Frequency
RIE	Reactive Ion Etching
RIN	Relative Intensity Noise
RTA	Rapid Thermal Annealing
RW	Ridge Waveguide
SA	Saturable Absorber
SiN	Silicon Nitride
SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
TBP	Time-Bandwidth Product
TEC	Thermo-Electric Cooler
QD	Quantum-Dot
QW	Quantum-Well
WDM	Wavelength-Division-Multiplexing

CHAPTER 1: INTRODUCTION

1.1 Motivations

As clock rates increase with the number of transistors in microprocessors, delay and thermal management in electrical interconnects have become a more serious issue, because of the decrease in the dielectric constant and the increase in the resistance of the metals that form interconnects due to shrinking dimensions. It is expected that at more than 10 GHz, the electrical interconnect will soon impose a major limitation (bottleneck) on improving clocking performance in the digital timing environment. Accordingly, much research efforts have been directed to optical interconnects. In 2004 Intel Corp. developed an optical interconnect architecture for chip-to-chip interconnects [1].

Mode-locked lasers (MLLs) are an attractive source for clocking signals in optical interconnects because of picosecond pulse trains, low timing jitter, and the synchronization ability to an external optical or electronic signal. Optical clock can distribute master clock signals to other ports with little distortion and small timing jitter [2]. Authors in [3,4] demonstrated significant performance improvements, such as receiver sensitivity enhancement, in a chip-to-chip optical interconnect by employing a modelocked laser.

The mode-locked lasers based on quantum-well (QW) and bulk semiconductor lasers have widely been studied [5] due to their excellent performance in many areas. Compared to other types of lasers, semiconductor lasers have many advantages, such as compact size, direct pumping by current injection, low power consumption owing to the high wall-plug efficiency [6], wide range of wavelength emission from UV to mid-IR, reliability and ease of high speed

direct modulation, and integration capability with other optoelectronic devices. The drawbacks of semiconductor lasers are beam quality, temperature sensitivity, and limited pulse energy in the pulsed operation due to their short carrier lifetimes of ~1 ns or less. Although achieving high-peak power and high-pulse energy is rather limited, the above mentioned advantages make them very useful as compact sources of high repetition rates due to their fast recombination time with high-average power.

Applications which can benefit from semiconductor lasers are classified in a time and a frequency domain. Time domain applications include short pulse generation, high-bit rate optical telecommunication, high-speed photonic analog-to-digital converter, optical sampling system, precision ranging and laser radar, optical clock for high speed optical network and interconnect, and photonic switching. Frequency domain applications include current and emerging areas, such as ultrabroadband wavelength-division-multiplexing (WDM), optical comb source, photonic microwave frequency sources, arbitrary waveform generation, frequency metrology, coherent optical communication, and optical code division multiple access (OCDMA) for secure communication.

In all applications, system performance critically depends on the quality of the optical pulses. Timing jitter and energy fluctuation are often limiting factors for the performance of a device or system. Especially timing jitter must be reduced as much as possible. Short pulse width for timing resolution and high beam power are also necessary for practical applications of MLLs.

Recently, lasers and semiconductor optical amplifiers (SOAs) based on quantum-dot (QD) materials have attracted much attention as next-generation light sources owing to their much improved performance compared to bulk/quantum-well (QW) counterparts. QD lasers and SOAs have shown remarkable properties;

- Reduced temperature sensitivity of threshold current. Removal of temperature controller can reduce the manufacturing cost significantly.
- Low threshold current density [7] and high wall plug efficiency lead to low power consumption
- Small linewidth enhancement factor (LEF) and the nature of inhomogeneous broadening of the QD gain material have a great potential to make QD mode-locked lasers a good candidate as a source for ultrashort and low noise mode-locked pulse generation.
 Feedback insensitivity and suppression of beam filamentation in broad area high power lasers [8, 9] may benefit from the small LEF.
- Broad gain spectrum due to the inherent dot size fluctuation during the growth process of self-assembled QDs. Ultrawide-band (120 nm) in a QD-SOA, which is the widest among all kinds of optical amplifiers, was demonstrated. [10]. The broad gain spectrum is very attractive in several applications, such as lasers with a wide tuning range for WDM and spectroscopy, and mode-locked lasers for short pulse generation.
- Ultrafast gain recovery time; a fast carrier capture of only several picoseconds showing that QD lasers are well suited for high-speed applications. The slow response of carrier recovery time (tens of ps) in bulk/QW SOAs manifests pattern effects in amplified signals, and the output power is dramatically reduced at high modulation speeds. [11,12]
- High saturation power and low noise figure: SOAs with gain of >20 dB, NF < 7 dB, saturation power of > 19 dBm were demonstrated [10].
- Higher tolerance to intentional degradation due to carrier localization in QDs; less susceptible to dislocations originating at the interface with substrate, and reduced facet surface overheating [13].

Owing to these exce llent performances, as discussed so far, QD-based MLLs are of interest for much improved performance as compared to conventional QW/bulk devices. In this dissertation we design and fabricate QD lasers and SOAs, and exploit the performance of various mode-locked lasers.

1.2 Dissertation Statement and Outline

This dissertation is organized as follows.

In chapter 1, the motivation of this work was presented. Fundamental issues of semiconductor QD model-locked lasers, such as the effect of quantum confinement, LEF and linewidth, the effect of the internal loss on noise and device length, mode-locking techniques, and the effects of dispersion and self phase modulation (SPM) are addressed in chapter 2.

Chapter 3 begins with the description of the QD wafer structure we used in this study. From the waveguide theories, design guidelines are developed for the single mode operation with suppressed reflection from waveguide discontinuities. The device fabrication procedure is explained, followed by the characteristics of FP laser, SOA, and monolithic two-section devices.

In Chapter 4, we study an external cavity mode-locked QD two-section diode laser and the performance of external pulse amplification and compression. Ultrashort, high power, and high quality pulse trains are obtained after optical amplification with a multilayer high-gain QD-SOA followed by a grating-based dispersion compensator. Addition of the dispersion compensator provides access to both positive and negative dispersion, allowing the measurement of the sign and magnitude of pulse chirp.

Chapter 5 covers the experimental investigations of noises in QD mode-locked lasers. The noise of MLLs and its measurement techniques are introduced. The timing jitter of hybrid mode locked QD mode-locked lasers and the average linewidth of longitudinal modes are measured. It leads to a conclusion that the low timing jitter of hybrid QD mode-locked lasers is a result of more than one order of magnitude reduction in the linewidth. Single longitudinal mode in the laser is filtered out by using a diffraction grating, and the modal relative intensity noise (RIN) was measured. Also we present the ultralow noise performance of an actively modelocked unidirectional ring laser based on a QD SOA as a gain medium.

Chapter 6, we demonstrated an opto-electronic oscillator (OEO) and coupled optoelectronic oscillators (COEO). The performance of the COEOs based on an active mode-locked ring laser and a two-section mode-locked laser is investigated. The phase noise of the COEO is measured by the photonic delay line frequency discriminator method. Based on this study we discuss prospects of COEO as a low noise optical pulse source.

Chapter 7 offers a brief summary of the achievements, as well as outlook/suggestions for future investigations.

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CHAPTER 2: REVIEW OF SEMICONDUCTOR LASER MODE-LOCKING

2.1 Quantum Dot Material

Double-hetero (DH) lasers consist of an active layer sandwiched between two high-gap cladding layers. The active-layer thickness is typically in the range of $0.1 - 0.3 \mu m$. If the carrier motion in a solid is confined in a layer of a thickness of the order of the carrier's de Broglie wavelength (~10 nm), one observes significant quantization effects due to the wave nature of the carriers. The quantization effects profoundly change the energy band structure and the behavior of the interaction between photons and charge carriers [1]. Figure 2-1 shows the effect of quantum confinement on density of states (DOS) for different structures.



Fig.2 - 1: Shape of active region and density of states versus energy level;

Bulk, Quantum well, Quantum wire, and Quantum dot. The crossed regions denote filled states.

The major benefit brought about by the greatly reduced active volume is a greatly reduced threshold current; the total number of carriers needed to achieve transparency density is reduced roughly by the ratio of the active volume. The free carrier absorption coefficient is also reduced by the same factor. The second benefit is a temperature insensitive lasing operation; because of the difficulty to thermally excite carriers due to large energy separation between ground and excited states. Another advantage is that electrons are spread over a smaller energy range with a high density at the peak gain. As a result population inversion is achieved with a lower injected carrier density [2-4].

The most efficient growing mechanism of QDs up to now, the modified Stranski-Krastanow growth mechanism driven by self-organization phenomena at the surface of strongly strained heterostructures was realized at the beginning of the 1990s. Material composition and growth conditions determine the size, shape, orientation, and strain. This technology made it possible to fabricate large densities of quantum dots easily and fast [5].

2.2 Linewidth Enhancement Factor and Linewidth in Semiconductor Lasers

In most gas and solid-state laser materials, atoms or molecules do not interact with each other. Thus increasing the number of population-inverted atoms or molecules has no effect on the refractive index. In semiconductor lasers, consisting of high concentration of interacting carriers, however, both refractive index and gain depends on carrier density, *N*. Any changes of the gain (imaginary part of the susceptibility) due to an injected carrier concentration will be accompanied by a change of the refractive index (real part of the susceptibility), which is given by the Kramers-Kronig relation [6]

$$\Delta n(\omega, N) = \frac{2ch}{\pi e^2} P \int_0^\infty \frac{\Delta g(\omega', N) d\omega'}{\omega'^2 - \omega^2}$$

where ω is the photon frequency, g is the gain (or loss), h is Planck's constant, c is the speed of light, and P indicates the principal value of the integral. The linewidth enhancement factor (LEF) (or α -factor, also known as anti-guiding factor), is defined as the ratio of derivative of the real and imaginary parts of the dielectric susceptibility with respect to carrier density N [7]:

$$\alpha = -\frac{d[\operatorname{Re}\{\chi\}]/dN}{d[\operatorname{Im}\{\chi\}]/dN} = -\frac{4\pi}{\lambda} \cdot \frac{dn(\omega, N)/dN}{dg(\omega, N)/dN}$$

The α -factor is one of the main features that distinguish the behavior of semiconductor lasers with respect to other types of lasers. The α -factor influences several fundamental aspects of semiconductor lasers, such as linewidth, dynamic response characteristics, chirp under current modulation, self-focusing and filamentation in broad-area high power devices, and optical feedback sensitivity. The pulse dynamics of mode-locked lasers is also greatly influenced by the α -factor. It introduces a coupling between the amplitude and the phase fluctuations of the electric field. An extensive review of the early works was presented by Osinski and Buus [8].

The α -factor for bulk DH lasers typically ranges between about 4 and 8 [8]. Lower values of α are found in QW lasers, because the differential gain in QW structure is significantly larger than that of DH, while the differential index is comparable. A brief overview and comparison of the measurement techniques are given in [9]. In QW lasers, it may be possible to achieve α =0 by the simultaneous use of strain, *p*-doping in the active region, and detuning the operation wavelength to a wavelength slightly shorter than that for maximum gain [10]. The QD gain media have atom-like density of states, and gain spectrum is symmetrical. From the Kramers–Kronig relation, a symmetric gain spectrum will yield α =0 at the peak gain because here the index of refraction will not change with carrier density [11]. The small α of QD gain media has been measured below threshold current density. However the presence of excited states and wetting layer results in asymmetric gain profile, leading to nonzero α in real dots.

In a semiconductor laser, the amplitude and phase of the lasing field are strongly coupled through the carrier density in the active medium. The α -factor is a measure of the coupling strength. Henry expressed the phase as [7]

$$\phi = \phi_i + \phi_r$$

where ϕ_i is the instantaneous, truly random component due to spontaneous emission noise. It gives the Schalow-Townes linewidth which is proportional to the spontaneous emission rate. ϕ_r is the component due to the gain-phase coupling. The above-threshold spectral linewidth is derived by [7],

$$\Delta v = \frac{R(1+\alpha^2)}{4\pi I}$$

where *R* is the spontaneous emission rate into the oscillating mode, *I* is the intensity of light. The α^2 term is the dominant source of spectral linewidth broadening. The spontaneous emission has also significant influence on the spectral properties and the dynamic behavior of lasers. The level of spontaneous emission in semiconductor lasers is considerably larger than that of non-semiconductor lasers because of the high gain in semiconductors. The analysis of Henry [12] shows that,

$$R = KGn_{sp}F_R$$

where *G* is the saturated gain, F_R is a mirror factor which depends on the reflectivity of facets, and n_{sp} is the average occupation number which characterized the degree of the population inversion. A complete inversion corresponds to $n_{sp} = 1$. In SOAs, n_{sp} ranges from 1.4 to more than 4 depending on the pumping rate and the operating wavelength. For most diode lasers, experiments indicate that $n_{sp} \sim 2$.

The value of *R* also depends on the waveguide structure, through the excess noise factor, or Peterman's *K*-factor [13]. In index guide structure, *K*=1, while purely gain-guided structures $K=\sqrt{2}$. In mixed guiding, it `can be much higher. Thus details of the waveguide structure have a strong influence on the *R*.

2.3 Semiconductor Optical Amplifier (SOA)

Throughout this study, SOAs are extensively used both as a power amplifier and a gain element in external cavities, and play an important role for high power and low noise pulse generation. Accurate modelings of SOAs require the use of a self-consistent nonlinear model, the Rigrod analysis, to account for the spatial dependence of the optical intensity and carrier density [14]. The proper length of a SOA for low noise high gain amplification is, however, analyzed in a simplified model. Power evolution in the SOA is given by the following equation;

$$\frac{dP}{dz} = \left(\frac{g_0}{1 + P/P_s} - \alpha_i\right)P$$

where g_0 is the small signal gain, α_{i} is the internal loss, and P_s is the saturation power. Here $g_0 \gg \alpha_{i}$ is assumed. The initial power of amplified spontaneous emission (ASE) at the starting position in the SOA is very small, and the power increases exponentially. As the power grows over the P_s so that $P/P_s >> 1$, the power evolution equation becomes;

$$\frac{dP}{dz} = g_0 P_s$$

In this regime, power increases linearly. As the cavity length is increased over the absorption length, which is defined as $1/\alpha$ [6], the ASE power rapidly approaches to the maximum power that can be extracted from the amplifier, P_{Lim} ,

$$P_{Lim} = \left(\frac{g_0}{\alpha_i} - 1\right) P_s \sim \frac{g_0}{\alpha_i} P_s$$

Beyond this absorption length the power does not increases with length anymore since the gain is equal to the loss. The power evolution of ASE in this simple model is depicted in figure 2-2. As the level of ASE grows, it begins to saturate optical amplifier and reduce the signal gain, making the amplified signal noisy.



Fig.2 - 2: A simple model of growing ASE power in an optical amplifier.

The typical value of internal loss is $\alpha \sim 30$ /cm (bulk), ~ 10 /cm (QW). The typical length of FP LDs and SOAs is 0.3 mm – 1 mm in bulk/QW devices. In QD device, $\alpha \sim 1-5$ /cm, has been reported. As a consequence QD devices can be made much longer than conventional ones.

The effective spontaneous emission input power to the SOA is given by [15]

$$P_{in,eff} = h \, v \eta_{sp} K B_0$$

where B_0 is the optical bandwidth. The $P_{in,eff}$ is typically 1-10 µW. The gain of an amplifier starts to be saturated when the ASE level at the output of the amplifier approaches the saturation power of the amplifier.

The noise figure (NF) of a SOA is given by [16]

$$NF = 2n_{sp}\left(\frac{g_0}{g_0 - \alpha_i}\right)$$

where the coupling loss is not accounted. The dominant contribution of the noise figure comes from the spontaneous emission factor (or population-inversion factor), n_{sp} . Internal losses also reduce the available gain from g_0 to g_0 - α_i . Thus the signal-to-ratio is degraded at least by 3 dB even with an ideal amplifier (n_{sp} =1).

The noise figure of QW/bulk SOAs is relatively high compared with EDFA, which restricts the performance of SOAs as preamplifiers and the linear repeaters. Theoretical investigations show that QD-SOAs can exhibit superior characteristics regarding gain, power, and noise compared to conventional types of SOAs [17, 18]. High saturated output power, large gain, and lower noise figure of QD-SOAs have been verified experimentally [19]. Thus QD-SOAs may replace EDFAs in the future in communication applications.

2.4 Mode-Locking of Semiconductor Lasers

Mode-locking is a technique to generate coherent optical pulses from laser cavities, by organizing the phase of axial modes [20]. Mode-locking provides superior quality pulses to gain/Q-switching with respect to the amplitude and the timing jitter, as well as the achievable minimum pulse width. Two commonly used mode-locking techniques are active and passive mode-locking.

2.4.1 Active Mode Locking

Active mode locking (AML) is achieved by modulating the loss or gain medium of a laser. If driving frequency, f_m , is equal to the inverse of the round-trip time of an optical pulse in the cavity, it is called the fundamental mode-locking. The fundamental mode-locking is a simple method, yielding stable optical pulse trains.. On the other hand, to achieve a higher mode-locking rate with the same cavity, harmonic mode-locking is commonly employed in which RF modulation is applied at the harmonic of the fundamental cavity frequency.

2.4.2 Passive Mode Locking

The key element necessary for passive mode-locking (PML) is a nonlinear switching element, a saturable absorber (SA). The intensity transmission of a SA is plotted as a function of input intensity in figure 2-3. The leading edge of the pulse is attenuated due to absorption; as a result the width of an input pulse narrows after passage through the device.



Fig.2 - 3: Intensity transmission curve of a saturable absorber.

The SA can be created by different ways, such as, the semiconductor saturable absorber mirrors (SESAM) which uses excitonic absorption in multi-quantum well stacks [21,22], or ion implantation at the edge of a semiconductor gain medium [23]. Ion implantation decreases the carrier recombination time by introducing the recombination centers. But it induces damage to the material, leading to a long term reliability problem. The use of excitonic absorption mechanism works only over a narrow wavelength range.

Monolithic mode-locked lasers (MMLs) are the simplest device which can produce short pulses of picosecond durations, requiring no external modulation sources or external cavity optics. Figure 2-4 shows the schematic of the short pulse generation from a two section MML, where the repetition rate is set by the device length. Devices are easily made by the separation of top contacts and the proper design of the segment length [24]. This technique is applicable to any structure (bulk/QW/QD), and regardless of material, because it has a wide absorption bandwidth.



Fig.2 - 4: Monolithic two-section single chip device.

The reversed-biased segment behaves as a high speed p-i-n photodetector and is highly absorbing. Incoming pulse saturates the band-to-band absorption and the short segment becomes transparent. The reverse bias field quickly sweeps the stored charge out of the active region, and the loss of the SA is recovered very quickly to the original high attenuation state after passage of the optical pulse [25]. The fast recovery time supports very high frequency (>100 GHz) mode-locking. Monlolithic passive mode-locked lasers have been demonstrated up to 350 GHz in QW lasers [26].

The available pulse energy from a MLL is limited by the saturation energy of the gain;

$$E_{sat} = \frac{h v A}{(\partial g / \partial N)}$$

where *A* is the mode size, $\partial g / \partial N$ is the differential gain. The E_{sat} is inversely proportional to the differential gain. A lower differential gain leads to a higher E_{sat} , because the gain remains high during the passage of the optical pulse during amplification. The PML operates in a specific pulse energy range. The big challenge of the PML is the large timing jitter.
2.4.3 Hybrid Mode Locking

The hybrid mode-locking (HML) combines active and passive mode-locking. For certain applications, such as clocking in optical interconnects, it is desirable to have the optical pulse output synchronized to external signals. The HML offers the advantages of both the short pulse generation and the synchronized output due to the active modulation. The timing stability is also improved owing to the stable external modulation.

2.4.4 Description of Mode Locking

The total electric field from a laser cavity is written as a sum over longitudinal modes of the laser cavity;

$$E(t) = \sum E_n(t) \cos[\omega_n t + \phi_n(t)] ,$$

where ω_n is the frequency of the *n*-th modes, and ϕ_n is the phase. The amplitude of the mode $E_n(t)$ changes with time due to frequency drift relative to the center of the gain profile or mode-competition due to spontaneous emission. The phase ϕ_n fluctuates in a random way because the coherent time of the laser is finite. The resulting output is continuous wave (CW) with intensity fluctuation.

Mode-locking is a method where the phases are coupled each other by perturbation so that a definite phase relationship between the modes is established [20]. This coupling results from nonlinear frequency-conversion mechanisms inside gain media. The mode coupling can be achieved by modulation of either gain or loss. In general case, the correlated phase of longitudinal modes can be expressed as

$$\phi_n = \phi_0 + n \cdot \phi_1 + n^2 \cdot \phi_2 + \dots$$

Now, as a result of the coherent addition of modes, the laser generates pulse trains. The gain bandwidth Δv sets the ultimate limit on the pulse width. Since the gain bandwidth of semiconductor lasers is quite large, pulses shorter than 100 fs are possible in principle. In practice achievable pulse width is strongly influenced by the interaction of cavity dispersion and self-phase modulation. Dispersion produces unequal spacing of the longitudinal cavity modes, which interferes with the coherent locking of modes, and hinders the shortening of the pulse width.

The self phase modulation (SPM) significantly affects the pulse propagation [24]. The SPM is caused by saturation of gain and absorption. When a pulse propagates a gain medium with an input energy close to the saturation energy, the gain and thus the carrier density is reduced. The drop in carrier density causes an increase in the index of refraction which in turn phase modulates the optical pulse, and results in a drop of the instantaneous frequency.

The SPM is the dominant mechanism for excess bandwidth production beyond the Fourier transform limit in mode-locked semiconductor lasers. It is expected that the SPM may be reduced in QD gain media, due to the reduced linewidth enhancement factor.

19

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CHAPTER 3: DEVICE DESIGN, FABRICATION, AND CHARACTERIZATION

3.1 Structure of the QD Wafer

The layer structure from which all devices are fabricated is shown in Table 3-1. The QD laser and amplifier epi structure was grown by molecular beam epitaxy (MBE) at a low temperature on an n+GaAs substrate by NL Nanosemiconductor GmbH, in Germany. It consists of a high doped GaAs p-metal contact layer of 200 nm thick, 1.5μ m thick p-AlGaAs cladding layers, active and waveguide layers consisting of InAs quantum dots, AlGaAs n-cladding layers, and a high doped n-GaAs substrate. The active region consists of 10 layers of self-assembled InAs/GaAs quantum dots, covered with 5nm In_{0.15}Ga_{0.85}As (wetting) layer. Ten layers of QDs are stacked with a separation of 33 nm of GaAs as barrier material

	QD wafer structure								
Layer	Material	Group	Repeat	Mole fraction		Thickness	Doping	Туре	Dopant
				start	finish	(nm)			
12	GaAs					200	1e20	Р	С
11	Al(x)Ga(1-x)As			0.35	0	15	1e19	Р	С
10	Al(x)Ga(1-x)As			0.35		1000	1e18	Р	С
9	Al(x)Ga(1-x)As			0.35		500	5e17	Р	С
8	GaAs	1	10			33		U/D	None
7	ln(x)Ga(1-x)As	1	10	0.15		5		U/D	None
6	InAs	1	10			0.8		U/D	None
5	GaAs					33		U/D	None
4	Al(x)Ga(1-x)As			0.35		500	5e17	N	Si
3	Al(x)Ga(1-x)As			0.35		1000	1e18	Ν	Si
2	Al(x)Ga(1-x)As			0	0.35	15	3e18	N	Si
1	GaAs					500	3e18	N	Si
0	GaAs substrate			N-	- GaAs 3 ir	nch			

Table 1: QD laser wafer structure.

The typical size of an InAs dot is on the order of 10 nm in the base length and 4-6 nm in the height, and it may contain 10^4 or more atoms [1]. InGaAs QDs in GaAs matrix are pyrimidally shaped with the typical surface density of about 5 x 10^{10} cm⁻². The dots lie on a residual two-dimensional film of In(Ga)As few monolayer thick, the wetting layer (WL). The wetting layer acts as a charge reservoir for quantum dots, and the carrier distribution in QDs is influenced by the wetting layer.

3.2 Waveguide Analysis and Device Design

The waveguide analysis based on the effective index approximation has been performed to find the proper parameters of the ridge waveguides for single transverse mode operation. SOA design requires more careful analysis on the residual reflectance, waveguide tilt angle, and intermode coupling. An analytic formula [2] is used to find the relation between the reflectivity of the fundamental mode and the tilt angle for a given waveguide width. For improved performance, several design features are studied by using analytic formula and a beam propagation simulation software (BeampropTM [3]). Further design features will be presented in the case of multisection devices.

3.2.1 Waveguide Analysis for Single Transverse Mode Operation

The refractive index of Al(x)Ga(1-x)As and Ga(x)In(1-x)As material systems were obtained from the [4]. The refractive index of Al_{0.35}Ga_{0.65}As used for p- and n-cladding is n=3.22, while that of GaAs and In_{0.15}Ga_{0.85}As is 3.43, 3.45, respectively, at the wavelength 1.27 µm. The existence of very thin layers in the simulation requires careful setting of the simulation

parameters, such as step size. In such case, the analytic expression of the averaged refractive index is applied [5];

$$n_{\parallel,av}^{2} = \frac{d_{1}n_{1}^{2} + d_{2}n_{2}^{2}}{d_{1} + d_{2}}$$

Then multilayers can be reduced to a few layers, making further analysis easy. The index difference as a function of etching depths was studied based on the effective index method, shown in figure 3-1 [6,7].



Fig.3 - 1: Index difference versus etching depth of waveguide.

For the index guiding effect to play an important role, as will be discussed later, the index difference ($\Delta n = n_2 - n_1$) must be larger than ~0.005, depending on materials [8]. In our case, etching depth larger than 1.4 µm is recommended.

The normalized waveguide thickness is defined by

$$D = k_0 (n_2^2 - n_1^2)^{1/2} d$$

If $D < \pi$, the waveguide can support only the lowest-order, the fundamental mode. The waveguide thickness *d* is chosen to satisfy the condition

$$d < \frac{\lambda_0}{2} (n_2^2 - n_1^2)^{-1/2}$$

For the condition $n_2=3.33$, $n_1=n_2-\Delta n$, $\Delta n=0.004$, the required waveguide width $d\sim3.9$ µm is obtained. If $\Delta n=0.005$, the *d* is 3.5 µm.

3.2.2 Ridge Waveguide (RW) Fabry-Perot Laser Diodes

The ridge waveguide is a quasi-index guide structure. The absence of material on either side of the ridge creates built-in index difference. Figure 3-2 shows the structures of a RW, which most devices in this study are based on. The ridge (or mesa) structure is formed by wet etching. SiN or BCB was used to confine the current injection.



Fig.3 - 2: Structure of a RW structure, (a) SiN, (b) BCB as an insulating layer.

The RW structure is simple to fabricate compared to index-guided structures, and provides a good single mode beam profile, small astigmatism of about 1 μ m, and negligible phase-front distortion. This quasi-index guided laser exhibits a transition from the gain-guided to the index-guided regime when Δn is increased. The details of the fundamental transverse mode operation requires a careful analysis of the mode stability, which is primarily determined by the RW geometry and layer composition, as well as gain guiding, carrier-induced antiguiding, and built-in index guiding etc. Agrawal showed that the transition occurs around $\Delta n \sim 0.005$ in a 1.3 µm. InGaAsP laser [8]. In the transition region the threshold current decreases rapidly, and the slope efficiency η_d increases, the lateral mode contracts, and the far field changes from a twinlobe to a single-lobe pattern.

3.2.3 Semiconductor Optical Amplifier (SOA)

In this study, SOAs are used both as a single pass optical amplifier and as a gain medium inside external laser cavities. The residual reflection at the facets can cause a laser to produce pulses with undesirable temporal structures and multiple pulses spaced at the round trip time of the cavity. Spectrally, the residual reflection produces a modulation in the gain spectrum that inhibits phase coherence across the wide bandwidth. Even facet reflectivities as low as 10^{-4} lead to significant trailing pulses [9].

The conditions for a very good anti-reflection (AR) coating on the facet of semiconductor laser diodes are extremely stringent. Very tight tolerances are required in order to achieve a reflectivity $<10^{-4}$. Although the lowest reflectivity achieved by an AR coating that has been used for a semiconductor laser is 2×10^{-4} [10], it is impractical for most coating systems. Extremely good control of thickness and material index is required to match the impedance of the laser mode and the air.

One very effective way to reduce the reflectance is to use angled facets, where most of the reflected light does not couple back into the guided modes of the waveguide. The angled

27

facet can be realized with an etched facet [11] or tilted waveguide. The following figure 3-3 shows an angled facet device.



Fig.3 - 3: SOA with tilted waveguide.

The residual reflectivity is derived in [2], where we briefly reproduce the result here. Assuming a Gaussian field distribution inside the waveguide, the effective modal reflectivity, defined by the portion of light reflected back into the waveguide, is

$$c \propto \int_{-\infty}^{\infty} (E_{1y} e^{i\theta\beta_1 x}) (E_{2y} e^{-i\theta\beta_2 x}) * dx \rightarrow \int_{-\infty}^{\infty} |E_y|^2 e^{2i\theta\beta x} dx$$
$$R_{eff} = R_f(\theta) |c|^2$$
$$R_{eff}(\theta) = R_f(\theta) e^{-(\pi n w \theta / \lambda)^2} ,$$

where R_f is the Fresnel reflectance, *n* the effective refractive index of the cladding, *w* mode width, and θ is the waveguide angle. The fundamental mode is expressed

$$E(x) = \cos(\kappa x - \frac{m\pi}{2}) \quad ,$$

inside the waveguide, and

$$E(x) = \cos(\kappa d) e^{-\gamma(|x|-d)}$$

in the cladding, showing that the fundamental mode is not a simple Gaussian function. The correct formula for the effective reflectance is then given by

,

$$R_{eff} = R_f(\theta) \left[\frac{WU^2 \{ [W^2 - (\theta\beta d)^2] \frac{\sin(2\theta\beta d)}{2\theta\beta d} + W\cos(2\theta\beta d) \} }{(1+W)[U^2 - (\theta\beta d)^2][W^2 + (\theta\beta d)^2]} \right]^2$$

where

$$U = \kappa d = \sqrt{n_1^2 k^2 - \beta^2} d$$
$$W = \gamma d = \sqrt{\beta^2 - n_2^2 k^2} d$$

The residual reflectivity is plotted in figure 3-4.



Fig.3 - 4: Residual reflectivity of the fundamental mode ($\Delta n=0.005$) for different waveguide width.

Reduction of R_{eff} can be achieved with a larger tilting angle of the waveguide, an increased mode width, and an improved AR coating. The R_{eff} does not decrease monotonically with tilting angles. In addition, the coupling efficiency of the light output to optical fibers will

decrease as the angle increases, because beam distortion increases with larger angles. The proper angle should be chosen for optimum performance.

SOAs with different tilting angles were fabricated. The actual reflectivity was measured as a function of tilt angles. A quick and simple method to determine the reflectivity of a laser facet is the threshold-shift method. The LI curves are compared in untilted and angled waveguide devices, or can be compared before and after the coating. The threshold current increases with decreasing reflectivities. This method is effective for devices with high-reflection (HR) coatings or with a small tilt angle.

Here we use the modulation index method developed by Kaminow-Eisenstein [12], which is based on the Hakki-Paoli technique [13]. The angled device is operated at the threshold current of the uncoated and un-angled device. The modulation index of the optical spectrum is calculated by

$$m = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad .$$

The residual reflectivity is then determined by

$$R_{eff} = R \left(\frac{1 - \sqrt{1 - m^2}}{m} \right)^2 ,$$

where *R* is the reflectivity of the un-angled/uncoated device. Figure 3-5 shows the residual reflectivity versus tilt angles, determined by the Kaminow-Eisenstein method.



Fig.3 - 5: Residual reflectivity versus tilt angles, determined by the Kaminow-Eisenstein method.

An effective way to decrease the R_{eff} while keeping dominant single mode in the waveguide is proposed in Ref [14], shown in figure 3-6. The idea is to taper the waveguide near the facets. This keeps single mode in most region of the device, and reduces back-reflected light by increased mode size at the facet.



Fig.3 - 6: Tapered SOA near facets, proposed in [14].

To determine the proper taper shape and length, a beam propagation method (BPM) simulation software (BeamPropTM) was used. When the waveguide width abruptly changes, beam is scattered and higher order modes are excited, as shown in figure 3-7. To avoid the

discontinuity of wave propagation, the width of the tapered section must increase adiabatically. In the following, the sudden change of the waveguide width is compared to the smooth transition.

Figure 3-8 (a) and (b) show the transition probability of m=0 to m=0 mode, and m=0 to m=2 mode for different taper lengths. The transition probability from other modes to the fundamental mode (m=0) is maximized, and the transition probability to the higher order mode (m=2) is minimized when the tapered region is longer than 50 µm.



Fig.3 - 7: BPM simulation with different transient length, (a) L=0 μ m; corresponds to the abrupt change of the waveguide width, (b) L=40 μ m; slow change of the waveguide width.



Fig.3 - 8: Power conversion efficiency for different taper lengths, (a) $0^{\text{th}} - 0^{\text{th}} \mod (b) 0^{\text{th}} - 2^{\text{nd}} \mod (b) 0^{\text{th}}$

3.2.4 Monolithic Mode-Locked Laser (MML) Diode

The general trend of pulse shortening and broadening in MML diodes due to the different lengths of the SA was discussed, and numerical simulation was performed in [15]. Some of the results are summarized here;

- SA width increase \rightarrow pulse shortens.
- Gain width increase \rightarrow pulse broadens.
- The longer the SA, the better the pulse shortening per pass.
- The longer the SA, the larger the gain required from the gain.
- The larger the ratio in saturation energies, the stronger the pulse shortening per pass.
- Long SA, self-colliding effect is diminished, leading to a higher bleaching energy and wider pulse width.
- Too long SA: required long gain, or high gain. Not practical, and ASE will become large enough to cause saturation of the gain.

- Long SA: more susceptible to the self-pulsation.
- Too short SA: incomplete mode-locking occurs (no pulse shortening).

The optimum length of the SA should be chosen for best performance. Furthermore, the uncertainty of required waveguide dimensions should be taken into account, considering that current (charge carriers) injection changes the refractive index, and that the accurate control of the waveguide width and height through wet etching process is not easy. Thus various waveguide shapes and dimensions were incorporated in the mask design.

The schematic of the first design of two-section mode-locked laser chips is shown in figure 3-9. One end of the waveguide is tilted to avoid the residual back-reflection. Another facet plays a role of a cavity mirror end.



Fig.3 - 9: Design of the waveguide in the first generation MML diode.

The size of the gap affects the waveguide loss. The power loss at the gap is calculated using the waveguide mode coupling efficiency formula. The loss depends on the waveguide widths. The gap must be smaller than 15 μ m for 4 μ m waveguide to keep the loss less than 5%. The gap between the SA and the gain section electrically isolates the sections. This original design uncovered a serious problem due to the etched gap between the SA and the gain section. The gap provided the physical discreteness of the waveguide. The wave reflection from the gap can greatly hinder the mode-locking performance. Figure 3-10 shows the detrimental effect of the reflection at the gap, as an example. The optical spectrum shows 5 nm modulation period,

which originates from the gap reflection. The big spectral modulation prevents the device from good mode-locking.

One solution to this problem is to tilt the edge of waveguide around the gap. The tilt angle of about 7 degree can significantly reduce the back-reflection into the waveguide. In addition, the residual reflection and the loss can be reduced by tapering the waveguide edge. It should be noted, however, that the accurate control of the edge shape is difficult in wet etching.



Fig.3 - 10: (a) Optical spectrum which shows the detrimental effect of the reflection at the gap, (b) zoom-in.

In the above solution, the gap is etched simultaneously with the RW. In this case the depth of the gap is not controlled independently. If the cladding layer is etched too much, the back reflection cannot be avoided at the gap. The new solution is proposed here; the gap can be made separately from the RW formation process, by modifying the mask and fabrication procedure, as depicted in figure 3-11. First, RW is formed by the wet etching process without the gap. Continue all the fabrication processes till the thinning stage. Since the metal contacts on the

SA are separated from the metal contacts on the gain section, the top surface of the gap is exposed to the air. Then the heavily-doped contact layer can be etch-away, by dipping the wafer into wet etchants. The etching depth is controlled by etching time. The metal contacts on the SA and gain section will play a role of a mask during the wet etching process.



Fig.3 - 11: Another solution to reduce the back-reflection at the gap.

The top contact layer is etched separately with the ridge forming process.

Further improvement is possible by introducing more loss to higher transverse modes. Increasing the curvature of the waveguide induces more radiation loss for m=1 mode than for m=0 mode. If the radius of curvature > 3000 mm, the bending loss of m=0 mode is negligible, while higher modes experience more loss. By incorporating the above mentioned aspects, the following waveguide design (Figure 3-12) was obtained.



Fig.3 - 12: Final design of the waveguides of two section devices.

One drawback of a curved waveguide is that it does not follow a crystallographic axis. Since wet etching produces waveguides with higher edge roughness due to etch anisotropy compared to the dry etching methods, careful fabrication is required.

The parasitic capacitance and inductance of high speed driving circuitry determine how fast one can modulate the waveguide section. The size of the metal pads is minimized to minimize the parasitic capacitance. High speed probe was used instead of Au-wiring to minimize the parasitic inductance.

3.3 Device Fabrication Procedure

Based on the analysis given in the previous section, a photomask for lithography is designed. LEdit of Tanner Research Co.[16] or Autocad was used to draw waveguide and metal

patterns. The GDSII format file generated by the software was sent to a photomask company for pattern generation on a chrome-coated silica glass.

The overall fabrication steps to make the RW devices are summarized as follows:

- Wafer cut
- Surface cleaning
- PECVD: SiN deposition
- Photoresist (PR) spinning and lithography, descum
- Wet etching, cleaning
- RIE: Remove SiN mask
- BCB planarization: spinning, curing, etching
- Lithography for metal liftoff process
- P-side metallization, liftoff, and RTA
- Thinning and polishing
- N-side metallization and RTA
- Cleaving into bar/chips, AR coating,
- Mounting, wiring

3.3.1 Wafer cut

As a first step, it is necessary to identify the major and minor axises of the wafer. The orientation of the each axis is shown in figure 3-13. The QD wafer we used follows the EJ standard. The etch rate depends on the density of semiconductor atoms, leading to different etch profiles depending on the waveguide direction. Etch rate in (100) plane is faster than in (111).



Fig.3 - 13: Wafer orientation. US standard and EJ standard.

3.3.2 Cleaning: surface preparation

The wafer is sequently soaked into acetone, methanol, and iso-propanol for 5 min at 100 $^{\circ}$ C each to remove organic residues and inorganic dust particles. Then the wafer is rinsed in deionized H₂O and dried with N₂ gas. After developing the photoresist (PR) in the lithography process, a short O₂-plasma ash (called descum process) in RIE chamber needs to be done to remove any organic residues from the developed PR.

3.3.3. Dielectric thin film deposition and removal

SiN of 200 nm thick is deposited on the wafer by the Plasma Therm PECVD (Plasma Enhanced Chemical Vapor Deposition) at 250 °C. Approximate thickness of the thin film can be estimated by observing the color of the film. It should be noted that the film thickness varies with the substrate position on the grounded electrode. The reaction chamber needs frequent cleanings because of the build up of deposited dielectric on the electrodes, giving a high concentration of dust.

Prior to etching the SiN, a 20 second oxygen descum is performed to clean up the PR edges, if needed. The SiN film is removed in the Plasma Therm RIE (Reactive Ion Etching) chamber. The gases include a highly reactive species such as oxygen and a halogen compound (CF₄). CF₄ plasma etches SiN but does not etch PR. The etch rate depends on RF power, gas flow rate, chamber pressure, number of wafers being etched, position of wafers, etch time, and area exposed/pattern geometry

3.3.4 Lithography

PRs are most sensitive to light in the UV part of the spectrum. Positive resists, Microposit PR1813 or PR1805, and negative resists, Futurrex NR7-1500P, NR7-500P, NR7-1000P were mainly used. These resists have about 0.5 µm resolution. The mercury lamp was used as a UV radiation source. Exposure was performed with the Karl Suss MJB3 contact mask aligner without using filters.

Lithography steps for PR1805 are summarized as follows:

- 1. Spin 4500 rpm/40s
- 2. 120 °C hotplate pre-bake to remove excess solvents, 4 min
- Exposure 3.7 sec. Minimum (threshold exposure) energy is required for complete removal of the resist during the development stage. The energy threshold of PR1805 is 150 mJ/cm²
- 4. Develop with AZ351, 351: DI=1:6, 17 sec (DI: deionized water)
- 5. 120 °C post-bake, 4 min
- 6. To remove the resist, boil in acetone, 5 min.
- NR7-1500P was used for the metal liftoff process:

- 1. Spin 5000 rpm/40 sec. then thickness is in the range of $1.14 \,\mu\text{m} 1.26 \,\mu\text{m}$
- 2. 150 °C hotplate pre-bake, 1 min
- 3. Exposure 5.3 sec. Sensitivity is 200 mJ/cm² @ 365 nm
- 4. 100 °C post-bake, 1 min
- 5. RD6 12 sec
- 6. Rinse in DI water
- 7. Removal of the resist in the resist remover RR2 or in acetone.

And short oxygen plasma was used to remove any unwanted organic materials from the sample.

3.3.5 Wet etching

The ridge waveguide can be formed by wet chemical etching or by dry etching. For etching InP, the wet etching is preferable, since it is simpler to set up and perform, and gives very smooth sidewalls. For etching GaAs, dry etching is commonly employed. In this study, we used the wet etching method for GaAs-based semiconductors.

Many combinations of chemicals can be used to form a waveguide. Wet etchants typically use three basic constituents: oxidizing agents, complexing agents and a dilutant [17]. Oxidizing agents such as H_2O_2 oxidize both Ga and As separately. Complexing agents, such as H_2SO_4 , H_3PO_4 , HCl, NH₄OH, Citric acid dissolve oxides. H2O or methanol are used as a dilutant. In this study, we used mostly H_3PO_4 : H_2O_2 : $H_2O=1:2:50$ for GaAs/AlGaAs etching. It takes about 12 minutes to form a 1.5 µm height waveguide.

The thickness of waveguides was measured with the Tencor profilometer. Figure 3-14 shows a SEM photo of a ridge structure. It shows an overhang of the top-contact layer GaAs

41

after wet etching. Because of the overhang, the metal connection is not formed between the ridge top and the metal pad



Fig.3 - 14: Scanning electron micrograph (SEM) image of a waveguide formed in the wet-etching step. The etchant is H₃PO₄:H₂O₂:H₂O=1:2:50.

This problem can be overcome in three ways. Different chemicals were found [19]. The mixture H_3PO_4 : H_2O_2 :Methanol: $H_2O = 0.75$:1:1:3 successfully removed the overhang, as shown in figure 3-15. PR1813 was used as an etching mask before etching.

The first problem of this solution is that sidewalls are not smooth, leading to a higher waveguide optical loss. Diluting can improve the smoothness but produces the overhang. Other problem is that the bottom of the ridge is very wide.

Another solution is a two-step wet etching method using GaAs selective etchants. After forming the ridge waveguide, the wafer was put into NH₄OH:H₂O₂:H₂O=1:5:20 solution for a short time (5-10 sec) with PR or SiN as an etching mask. Using a non-selective enchant, Bromine (Br, HBr), is also a possible solution. But it is an extremely toxic and caustic chemical.



Fig.3 - 15: Scanning electron micrograph (SEM) image of a waveguide formed in the wet-etching step. The etchant is H_3PO_4 : H_2O_2 :Methanol: $H_2O = 0.75$:1:1:3.

3.3.6 BCB polyimide planarization: spinning, curing, etching

To confine current flow around the active waveguide region, an insulating layer, such as SiN, SiO₂, can be deposited, and the lithography is done to open a narrow stripe on the waveguide. Here the BCB film is used as an insulating layer for higher speed modulation capability due to its lower dielectric constant. An adhesion promoter is applied at 4000 rpm/40 sec, followed by BCB spin at 4000 rpm, 40 sec. The polyimide is then cured in a programmable oven in a N₂ ambient at 250 ^{o}C for more than 1 hour. The sample is loaded into the RIE etching chamber, and cyclotine.prc is run to etch the BCB for 9-10 minutes. Once desired height is reached, dip the sample in the ash remover REZI28 at 50 ^{o}C , 5 minutes to remove residues.

The degree of planarization is important in terms of device yields. A greater degree of planarization can be achieved by spinning a thick photoresist layer on top of the polyimide. PR and polyimide etch in O_2 plasma at nearly the same rate.

3.3.7 P-side Ohmic contact: metallization and liftoff, RTA

A metal stripe and pads over the waveguide are created by the metal liftoff process (Figure 3-16). Surface cleaning is critical for high quality ohmic contacts. Thin oxide typically present on a surface can be a major obstacle to a good ohmic contact.



Fig.3 - 16: Metal liftoff process.

The sample is attached on a piece of glass substrate using PR1813. Bake it at 100 °C for 1 minute. Before the evaporation of the metal, oxides should be removed from the wafer surface. The oxide removal is a critical step, because the adhesion of metals to surface oxides is very poor. An oxide layer between the wafer and the contact metal can cause a undesirably high electrical resistance. To remove any oxides from GaAs and to expose a clean surface for metallization, dip the sample in a Hcl:H₂O=1:1 solution for 30 sec, and a rinse in H₂O followed by a blow dry with N₂.

The sample is quickly loaded into a metal evaporator to minimize new surface oxide formation. Metal contacts are deposited after the pressure has reached at least 10⁻⁶ Torr. There

are many metal systems available for good ohmic contacts [18]. Two systems for p-type Ohmic contact were tested:

• Au/Zn/Au (2 nm/ 20 nm/ 200 nm)

The first Au layer provides good adhesion. This layer also works as nuclei for the Zn atoms and form a flat surface. The first 2 nm thick Au layer permits easy penetration of Zn into the GaAs bulk during alloying. Zn works as an additional p^+ dopant. The top 200 nm thick Au layer prohibits the vaporization of Zn during alloying and makes a uniform alloyed surface.

• Ti/Au or Ti/Pt/Au

Ti provides excellent adhesion between the semiconductor and Au layer. It is also a barrier component. Pt is a diffusion blocking layer that prevents the gold from diffusing into the semiconductor during the high temperature processes used in the fabrication (annealing). The gold is the actual bonding medium which provides the device contact. For thick Au layer to provide rigid mechanical contact, electroplating can be done. After metallization is done, the sample was removed from the carrier wafer by soaking it in acetone. The sample is then put into acetone or resist remover to liftoff the unwanted gold from the sample.

The sample is loaded into a rapid thermal annealer (RTA). Temperature rapidly increases up to 400 $^{\circ}$ C in an N₂ gas ambient for 1 min. Through this process different atoms chemically bond with each other to form a metal alloy. Rapid heating and cooling is used to obtain a low contact resistivity because unwanted compounds are formed during the heating and cooling transitions.

45

3.3.8 Wafer Thinning and polishing

Prior to the n-contact deposition, the wafer is thinned to improve both cleaving and heat conduction. The wafer is attached to a slide glass substrate with wax to protect it, thinned mechanically to a thickness of approximately 120 μ m using slurry of 5 μ m alumina grit and water, then polished in 0.3 μ m slurry

3.3.9 N-side metallization and RTA

For n-side metallization, Ni/Ge/Au metal layers are evaporated at the backside of the wafer. The n-contact consists of thermally evaporated Ni 2 nm, Ge 20 nm, and Au 200 nm. The Ni provides adhesion, plays a role of catalyser for GaAs and Au reaction, and provides the driving force for Ge diffusion. Ge works as a n⁺ dopant [18]. RTA is done at 400 °C in an N₂ gas ambient for $1 \sim 2$ min, after n-side metallization. The high temperature makes Zn/Ge diffuse into the semiconductor; leading to a good ohmic contact.

3.3.10 Cleaving into bar/chips, AR coating,

After the final alloying step, the wafer is cleaved into laser bars and single chips under a microscope using a micrometer controlled manual scriber (home-built using a diamond tip and XYZ micrometers). Most devices require anti-reflection (AR) coating on the facets. Facets must be immediately coated to protect the mirrors against corrosion. Because the equipments for dielectric evaporation were not available, the PECVD was tested to deposit SiN film on the facet. The refractive index of the SiO_xN_y film can, in principle, be adjusted between 1.45 (SiO₂) and 2.1 (Si₃N₄) by controlling the ratio of silane and ammonia. Actually the problem requires an extensive research in order to identify the ideal combination of processing parameters such as

46

reaction temperature, rf-power, gas flow ratios to fine tune optical and mechanical properties of the film.

For testing, a SiO_xN_y film was deposited on a GaAs wafer. The PECVD parameters were RF=150 W, T=300 °C, SiH=180 sccm, NH₃=4 sccm, N₂O=3.5 sccm, N₂=800 sccm. The film thickness was ~200 nm with 12 min of deposition time. Figure 3-17 shows the reflectance of a single-layer AR coated wafer with a target wavelength of 1550 nm.

The minimum reflectance of 0.5% was obtained, which is quite acceptable. The film thickness and the refractive-index can be determined by applying the "envelope method" [20]. However, thickness control was very hard due to dependence on chamber parameters, and sample position and heights. The AR coating on the real devices was very difficult to reproduce. In this experiment devices were sent to a company for high quality AR coating, if necessary. Figure 3-18 shows the picture of a ready-to-mount monolithic mode-locked laser device.



Fig.3 - 17: Reflectance of single-layer SiO_xN_y AR coating on GaAs-wafer with target wavelength of 1550 nm, measured with the Cary spectrophotometer.



Fig.3 - 18: A device picture of a ready-to-mount monolithic mode-locked laser device.

3.3.11. Mounting: die-bonding and wiring

Since the thermal conductivity of the GaAs substrate is low (44 W/mK), it is recommended to mount the junction-side down. FP lasers and SOAs are soldered p-side down on a gold-coated copper stud with Pb-In solders. A 2-mm long gold wire or ribbon then connects the diode to a gold-plated ceramic standoff, which provides a robust contact for connection to the external drive circuitry. The stud is then mounted onto a thermoelectric cooler through a copper-fixture. For more details, refer to [21].

Two-section devices are mounted n-side down on a stud. A modified microwave highspeed probe was used instead of wire bonding in order to minimize parasitic effects of high speed driving. The long gold wire introduces the parasitic inductance, leading to driving bandwidth limitation.

3.4 Device Characteristics

3.4.1 Characteristics of FP Laser Diodes

The FP LD is formed by cleaving the semiconductor substrate in a plane that is perpendicular to the narrow gain stripe. The facets remain uncoated. The internal reflection coefficient remains above ~30% due to its high refractive index (~3.6) even when the facets are uncoated. The FP LD was mounted on a Au-coated copper stud with a solder, and DC forward bias is applied through the Cascade probe. Temperature is controlled by the Lightwave temperature controller through a thermo-electric cooler (TEC). Heat removal from the active area is critical for CW lasing. Without soldering on a heat sink, devices shows big thermal behavior, and lasing occurs only in a pulsed current injection.

Figure 3-19 shows the light output versus currents and voltage versus currents for a 1 mm long FP laser diode.



Fig.3 - 19: (a) Light output vs currents (LI), and (b) voltage vs currents (VI) for a 1 mm FP LD.

The IV curve shows the typical behavior of laser diodes. The series resistance,

 $R_s = dV / dI$, above the laser threshold, was measured to be ~4 Ω in a rough linear approximation. Laser diodes should have as low a series resistance as possible to prevent heating of the device. The threshold current I_{th} for this 1 mm device was 20 mA. It increases as the device length,

The absorption loss in a laser cavity is one of the fundamental factors. Possible loss mechanisms in a semiconductor laser include free carrier absorption in the active region, cladding loss, and scattering loss at the interface in the waveguide. The threshold current and slope efficiency as a function of device length provide important information on the internal loss and the quantum efficiency of the device.

The slope efficiency dP/dI is converted into the external efficiency;

$$\eta_d \equiv \frac{e}{h\nu} \frac{dP_{out}}{dI} = \frac{\lambda[\mu m]}{1.24} \frac{dP_{out}[mW]}{dI[mA]}$$

where P_{out} is the output power (both side). The internal quantum efficiency and the internal loss are obtained by fitting the data to the simple relation [22];

$$\eta_d = \eta_i [1 + \frac{\alpha_i L}{\ln(1/R)}]^{-1}$$
, (3-1)

where η_d is the slope efficiency, η_i the internal quantum efficiency (represents the fraction of injected carriers that recombine in the active region). From the fitting (figure 3-20), we obtained α_i =1.1/cm, η_i =0.46. The internal loss of conventional broad area QW LDs are in the range of 10-15/cm, while 20-30 /cm for GaAs DH LDs.

The optical spectra were recorded with a single-mode-fiber-coupled spectrum analyzer with a resolution of 0.01 nm. To reduce back-reflections into the diode, the FC/APC type fiber with 8° angle, was used for fiber coupling. To increase the isolation, optical isolators can be

used. Figure 3-21 shows the optical spectrum of a 1 mm long FP LD above the threshold, showing the discrete longitudinal FP modes.



Fig.3 - 20: Inverse of the slope efficiency as a function of device length, and fit to Eq. (3-1).

The beam profile was measured using a CCD, shown in figure 3-21(b). The beam is a single mode both in horizontal and vertical direction. The substructure in vertical direction comes from the finite size of beam collecting lens, which has NA of about 0.5. The beam profile from the tilted waveguide is crescent shaped due to the wavefront tilting at the facet.



Fig.3 - 21: (a) Optical spectrum, (b) Beam profile, of a 1 mm long FP LD.

• Polarization

The beam was found to be predominantly TE. The possible origins are the flat shape, and compressive in-plane strain.

• GVD measurement of QD laser medium

From optical spectrums of a laser diode below the threshold, the refractive index is obtained, shown in figure 3-22 according to the following relations;

$$\Delta v = \frac{c}{2n_g d} \qquad \text{(Mode spacing)}$$
$$n_g = n - \lambda \left(\frac{\partial n}{\partial \lambda}\right) \qquad \text{(Group index)}$$
$$\text{GVD} = \frac{\partial n}{\partial \lambda} \qquad \text{(GVD)} \ .$$

A Labview code written by G. Shtengel [23] was used to extract the refractive index and its slope (group velocity dispersion, GVD) from the optical spectrum.



Fig.3 - 22: (a) ASE optical spectrum of a 2 mm QD FP laser didoe, (b) group index, ng.

The group index and the GVD at different current injections are plotted in figure 3-23. The average group refractive index of \sim 3.65 and GVD of -15 /nm were measured at 1267 nm wavelength.



Fig.3 - 23: (a) Group index, and (b) GVD of a 2 mm QD FP laser diode at 1267 nm wavelength.

• Linewidth Enhancement Factor (α -factor)

In this experiment we apply one of the most straightforward and popular methods which relies on the direct measurement of the gain and index change under the threshold current of a Fabry-Perot laser diode as the carrier density is varied. The measurement was performed using a high resolution optical spectrum analyzer. The quantity Δn was measured through the detection of the wavelength shift of longitudinal Fabry-Perot modes, while dg was obtained via the Hakki-Paoli method [13] by measuring the fringe contrast ratio of the amplified spontaneous emission.

The LEF is expressed as [25]

$$\alpha = -\frac{4\pi n}{\lambda^2} \cdot \frac{\Delta \lambda_{\text{peak}}}{\Delta g_{\text{net}}} = -\frac{2\pi}{L} \frac{1}{\delta \lambda_{\text{FP}}} \frac{\Delta \lambda_{\text{peak}}}{\Delta g_{\text{net}}} = \frac{4\pi}{v_g} \cdot \frac{\Delta v_{\text{peak}}}{\Delta g_{\text{net}}}$$
Here $\delta \lambda_{FP}$ is Fabry-Perot mode spacing. Accurate measurement is, however, rather limited by the sensitivity and the resolution of the optical spectrum analyzer, due to low level of ASE light and the fiber coupling loss.

The experiment was done below threshold. The QD FP LD used for this experiment was 2 mm long. It was mounted p-down on a thermo-electric-cooler (TEC) controlled copper heat sink. Removing the thermal effect is very important. Thus the device was operated at a constant room temperature in the pulsed mode (100 ns) using the AV-155C-C pulsed-current driver to avoid the self-heating effect. The light output from the laser was coupled into a single mode fiber and its spectrum was recorded with a high-resolution optical spectrum analyzer, Ando AQ6317 with 0.01 nm resolution. Figure 3-24 shows the change of the optical spectrum as the current level increases.



Fig.3 - 24: (a) Optical spectrums with different injection currents, (b) zoom-in.

The change of the refractive index was measured by reading the peak frequency shift of the FP modes. The gain of the FP device was measured using the Hakki-Paoli method [13]. Below the threshold the net gain is given by

$$g_{net} = \Gamma g - \alpha_i - \alpha_m = \frac{1}{L} \ln[\frac{\sqrt{(p^+ / p^-)} - 1}{\sqrt{(p^+ / p^-)} + 1}],$$

where p^- is the intensity of valley (local min) and p^+ is the intensity of peak (local max). From the ratio of the peak wavelength shift and the net gain shift, the α factor was obtained, as in figure 3-25.

This measurement shows that the α is approaching to zero near the threshold current, which is consistent with the results of [26-29]. The "material" α -factor, measured here, however, might give poor information regarding the "device" α -factor when laser dynamics is concerned.



Fig.3 - 25: (a) Wavelength shift and net gain change versus current, and (b) linewidth enhancement factor versus current.

3.4.2 Characteristics of QD-SOA

The laser output power and its optical spectrum of one facet were measured, in figure 3-26. The device was AR coated and mounted p-side up. The optical power of 0.18 mW at 200 mA was obtained from one facet. The spectrum of ASE gives the 28 nm FWHM, showing the capability of short pulse generation due to the broad gain bandwidth.



Fig.3 - 26: (a) LI, and (b) optical spectrum of a QD SOA.

At low currents, the optical power increases exponentially with increasing drive currents. Over 200 mA, thermal roll-over starts to show. The FP modes are not observed from the spectrum below 300 mA with 0.01 nm resolution. For a non-AR coated SOA, FP modes are observed in the case of small waveguide widths or small tilt angles. The log scale optical spectrum in figure 3-27 shows the effect of excited state transitions clearly. As the current increase, ground states are saturated, and the excited state transitions grow. The optical gain of a QD SOA was measured, and is shown in figure 3-28.



Fig.3 - 27: Optical spectrum of QD SOA versus injection current.



Fig.3 - 28: Optical gain versus output power.

The 19 dB gain and ~14.5 dBm saturation output power were measured. Although saturation powers as high as 100 mW have been reported for multiple-QW amplifiers [30], higher gain and saturation power are predicted from QD SOAs [31].

3.4.3 Characteristics of MML Diodes- Monolithic Device

The light output versus DC forward bias currents of a two-section external cavity laser is measured, and plotted in Figure 3-29. The length of device was 3 mm. Figure 3-29 (b) shows the hysterisys behavior, which is an indication of a nonlinear transmission characteristic of saturable absorbers. Other characteristics of this device will be discussed in later section.



Fig.3 - 29: (a) LI for different reverse bias currents, (b) LI showing the hysterisys behavior.

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CHAPTER 4: ULTRASHORT, HIGH PEAK POWER PULSE GENERATION FROM A MONOLITHIC MODE-LOCKED LASER

4.1 Introduction

The monolithic mode-locked laser based on QD gain-media (QD-MML) is of interest owing to the improved performance expected, as compared to conventional QW/bulk devices. Intensive studies on QD-MML have been reported [1-3]. Their broad gain bandwidth and reduced linewidth enhancement factor make them excellent candidates as sources of ultrashort [4], low noise pulses [5].

The repetition rate of MLL is determined by the device length. 40 GHz pulse trains can be generated from 1 mm long device. However, such high frequencies are still too high in present practical applications due to the increase of cost and complexity. The 10 GHz or lower frequency technologies are dominant now. One great advantage of QD lasers is that 10 GHz or lower frequency devices are completely feasible owing to the low internal loss, in contrast to conventional QW/bulk lasers [6]. It should be noted that modelocked operation of a 8-mm QD monolithic device at a 5 GHz repetition rate has been demonstrated [5]. Lower repetition rates require longer waveguides, which place severe requirements on material growth, processing uniformity, and cost.

External cavity designs are in common use for semiconductor laser mode-locking. The repetition rate is adjusted mechanically by changing the length of the external cavity (and driving frequency). Although they require the alignment of bulk optics, they have flexibility in constructing lasers by incorporating tuning elements, filter, etc. The formation of various cavity

topologies, such as linear, ring, sigma-type, theta-cavities, are also straightforward. This flexibility provides great access to many properties of laser. In this study, we focus on the external cavity configuration. For this purpose we fabricated two-section MLLs with curved waveguides.

From the master oscillator, high quality pulses are produced in a limited regime of DC current and reverse bias voltage on SA. To obtain low noise and high power pulse trains, the master-oscillator-power-amplifier (MOPA) architecture is a preferred approach which is well-known in the fields of gas or solid-state laser systems. We will use the MOPA architecture.

4.2 Laser Setup and Results

The two-section devices used for this study consist of a gain section and a saturable absorber section. The gain section is curved and terminated at an angle of 7° relative to the cleaved facet to minimize the back-reflection from the facet. The residual reflectivity from the curved waveguide was estimated to be less than 10^{-5} . The device length was 3mm with a 300 μ m long saturable absorber (SA) section. A ridge waveguide of 5 μ m in width was formed by standard lithography and wet-etching. The 15 μ m gap between two sections was chemically etched. The electrical isolation resistance between gain and absorber section was measured to be 6.4 k Ω . After cleaving the device, it was mounted on a gold-coated copper stud with p-side up, as cleaved.

An external cavity monolithic mode-locked semiconductor lasers (ECML), as shown in figure 4-1, was constructed out of a two-section device with a curved waveguide and an external mirror. The collimating lens with AR coated aspheric surfaces has a numerical aperture of 0.55

and the focal length 6.5 cm. The output coupler R=70 % was used. In this setup, the CW threshold was ~70 mA without reverse bias voltage.



Fig.4 - 1: Experimental setup. I - Isolator; OC – Output Coupler (R=70%); QD-ECML –
 Quantum Dot External Cavity Mode-Locked Laser;
 QD-SOA – Quantum Dot Semiconductor Optical Amplifier.

The pulses from the oscillator were amplified with a 3.2 mm long QD-SOA. The waveguide was angled by 7°, anti-reflection (AR) coated, and p-up mounted. Both the two-section device and SOA were kept at 20 °C using thermo-electric cooler control. The QD-SOA exhibited a thermal rollover over 300 mA. The maximum small signal gain and the output saturation power of the multilayer QD-SOA were measured to be 19 dB and 16 dBm, respectively, including the coupling loss, which is comparable to the performance of conventional SOAs. The amplified pulses were diagnosed by an optical spectrum analyzer with 0.1 nm resolution, a 14 GHz bandwidth photodetector followed by a microwave amplifier, a RF spectrum analyzer, a digital sampling scope, and a background-free autocorrelator.

The optical and RF spectrum of the high quality passive mode-locked pulses are shown in figure 4-2 (a) and 4-2 (b). The most optical spectra show that the center of mode-locked spectra

is shifted to long-wavelength side of the gain peak; it can be understood by considering that reverse-biases red-shift the band edge due to the Franz-Keldysh and the quantum-Stark effect [7]. The SPM also causes the red-shift of spectrum.



Fig.4 - 2: Spectrum of passive mode-locked pulses. DC=118 mA, Reverse bias voltage=-5V. (a) Optical spectrum, (b) RF spectrum.

Similar pulsewidths and energy were obtained over a wide range of repetition rates, between 2.4 and 6 GHz. The fundamental cavity frequency is set to be 4.95 GHz for further investigation. The average output power of 0.5 - 3mW was obtained from the mode-locked laser cavity. Clean mode-locked pulses were generated without relaxation oscillation over a broad range of DC currents and reverse bias voltage.

The noise side band in RF spectrum of passive-mode locked lasers depends on applied DC current on the gain section and revere bias voltage on the SA section. The figure 4-3 shows an example how the noise side band changes with the reverse bias voltage.



Fig.4 - 3: RF spectrum of PML. (a) 100 mA, -4 V (b) 100 mA, -5.6 V.

Hybrid mode-locking was performed by modulating the absorber section at the fundamental cavity-frequency with a sinusoidal RF input power of 16-20 dBm. The pulse width was found to be similar in both hybrid and passive mode-locking. The RF spectra of the PML and HML near the carrier frequency are shown in figure 4-4(a) and 4-4(b). The PML has a broad tone which indicates the mode-locked frequency itself is fluctuating. With RF power injection, the reduction of the noise side band is clearly seen. The pulse train displayed on sampling oscilloscope is shown in figure 4-5.

The pulse widths are measured with a nonlinear second-harmonic generation autocorrelator made by Femtochrome, Inc., which utilizes a modified Michelson interferometer to self probe the temporal intensity of ultrashort optical pulses. The FWHM of the autocorrelation trace of the pulses generated from the oscillator varies from a few ps to several tens of ps depending on bias condition. Figure 4-6 shows the pulse width change from 3.5 ps to 38 ps as a function of reverse bias voltage at a DC current of 118 mA. Near transform-limited pulses of 3.5 ps with 1.3 nm spectral width were obtained with a reverse bias voltage of -8V. However the pulse train quality degraded simultaneously, as manifested by the increased noise sidebands in the RF spectrum, and the pulse energy (average power) decreased significantly due to the high reverse bias. In addition, multiple pulses were formed at this high reverse bias. Robust pulses with the lowest noise sidebands in the RF spectrum were obtained at a reverse bias of about -5V and a DC current of 118mA.



Fig.4 - 4: Zoom-in RF spectrum of (a) passive mode-locked, (b) hybrid mode-locked pulse train.

RBW (resolution bandwidth).



Fig.4 - 5: Sampling trace of optical pulse trains.



Fig.4 - 6: (a) Normalized autocorrelation trace with different reverse bias voltage, (b) FWHM of autocorrelation signal versus reverse bias voltage on absorber section at DC=118mA.

The mode-locked pulses with the autocorrelation signal width of 15 ps with 3dB bandwidth of the optical spectrum of 3.1 nm. The corresponding time-bandwidth-product (TBP) of ~6 implies that the mode-locked pulses generated from the ECML are highly chirped. To compress the pulses and investigate the chirp sign and magnitude, a dual grating dispersion compensator was constructed, shown in figure 4-7. The internal telescope configuration was used to access both signs of chirp. The groove density of the grating was 1100 g/mm, and the insertion loss of the grating compensator after double pass was 5.4 dB.



Fig.4 - 7 Schematic of dual grating dispersion compensator in the 4-f system.

The output pulses of the master oscillator were sent to the grating compressor. The linear component of the chirp is compensated by changing the position of the second grating. The optimum pulse compression was achieved in the negative GVD region of the compressor, where the position for the second grating is outside the focal length. Figure 4-8 shows compressed pulse width versus the offset location of the second grating from the zero-dispersion position. Thus the output pulses of the monolithic ECML are positive- or frequency up-chirped, meaning that the instantaneous frequency rises with time.



Fig.4 - 8: Compressed pulse width versus the offset location of the second grating.



Fig.4 - 9: Autocorrelation signal of the compressed pulses.

As a result of the compression, 1.2 ps deconvolved pulsewidths, assuming a sech² pulse intensity profile are obtained. The TBP of 0.69 was achieved, which is about twice the Fourier-transform limit. Figure 4-9 shows the autocorrelation signal of the uncompressed and compressed pulses. The overlap between the experimental data and the fit shows high quality of compressed pulse shape without significant tails caused by nonlinear chirp. The average power after compression is 7.2 mW, implying that the peak power and energy of the compressed pulses are 1.22 W, and the 1.46 pJ, respectively.

4.3 Grating Coupled External Cavity

In this section, we show the wavelength tunability and pulse characteristics of the QD mode-locked laser by employing a diffraction grating as a center wavelength control element.

A grating coupled monolithic ECML with a fundamental cavity frequency of 2.5 GHz was built using a two section device and an external grating with 900 lines/mm groove density. The external cavity configuration is the standard Littrow setup where the first order diffracted output is feedback into the gain medium (figure 4-10). The light coming from the gain section was collimated to the grating. The facet of the SA side on the two-section device was used as an output coupler.



Fig.4 - 10: A grating coupled external cavity monolithic mode-locked laser.

The wavelength tuning is done by rotating the grating. The optical spectrum of the modelocked pulses, shown in figure 4-11, shows the broad tuning range of the center wavelength. The 3 dB optical bandwidth was ~0.4 nm, for both ground state (GS) and excited state (ES) transitions. The total tuning wavelength range is greatly extended because of the contribution from the ES transitions. The excited state transitions add more accessible bandwidth.



Fig.4 - 11: Optical spectrum of grating-coupled passive mode-locking, showing the wavelength tunability.

The quantum dot ES transitions possess interesting characteristics such as ultrafast gain recovery, higher differential gain, and negative linewidth enhancement factor [8]. The ES mode-locking was demonstrated first from a monolithic two section laser diode by control of the injection current and applying a reverse bias to force lasing to switch from the ground state to the excited state transition [9]. The use of the grating coupled monolithic ECML allows the independent study of the pulse forming characteristics in the excited state and ground state mode-locking regime.

4.4 Discussions

Mode-locking performance is affected by many parameters, such as the gain bandwidth, dispersion, SPM, the saturation energy of the saturable gain and absorber, the gain and absorber recovery time, and gain nonlinearities due to carrier heating or spectral hole burning. The changes in the carrier density induced by the time-dependent gain and absorption invariably lead to relatively-large time-dependent index of refraction for QW and bulk semiconductor active medium. The SPM results in considerable spectral and temporal change. The SPM-induced frequency chirp, $\Delta v(t)$, is related with α -factor, through [10]

$$\Delta v(\tau) \equiv \Delta v_{out}(\tau) - \Delta v_{in}(\tau) = \frac{\alpha}{4\pi} \frac{\partial h}{\partial t} ,$$

$$\Delta v(\tau) = -\frac{\alpha}{4\pi^{3/2} \tau_0} \frac{E_{in}}{E_{sat}} \exp\left[-\left(\frac{\tau}{\tau_0}\right)^2\right] (G(\tau) - 1) ,$$

where the integrated gain, h(t), is defined by $P_{out}(t) = P_{in}(t) \exp(h(t))$, and Gaussian pulse shape is assumed. The frequency chirp depends on α , G (gain/loss), pulse width (τ_0), saturation energy (E_{sat}), and input pulse energy (E_{in}). In absorbing media (G<1), the frequency shift is opposite to gain media (G>1).

To further investigate the chirp of the pulses generated from the laser cavity, we measured the magnitude of the chirp parameter as a function of driving currents and reverse bias voltages using a device with an absorber of 200 μ m long. The offset position of the second grating from zero dispersion providing the minimum pulse width is converted into the chirp parameter in units of ps/nm.

Figure 4-12 shows that the magnitude of up chirp increases with injection currents, and decreases with reverse bias voltages. The opposite trend is a consequence of the fact that the

phase modulation of an absorbing media due to amplitude-phase coupling has the sign opposite to that of the gain medium. This measurement shows that the total chirp can be controlled by changing the relative strength of the absorber and gain sections. The two mechanisms may cancel each other under special conditions, leading to transform-limited pulses [1], which is most likely to occur at high reverse bias voltages.



Fig.4 - 12: The chirp of pulses as a function of (a) driving currents and (b) reverse bias voltages.

The sign of the pulse chirp is up (positive)-chirp, as noted in the previous section. The up-chirped pulses are typically observed in electrically-pumped passive mode-locked semiconductor lasers based on QW/bulk medium [11] with only a few exceptions at very high-repetition rate [12]. The mechanism of the up-chirp, typically observed in electrically-pumped passive mode-locked semiconductor lasers based on QW/bulk medium, has theoretically been explained as a consequence of different α parameters in the gain and absorber section [13].

Measurements show that the magnitude of chirp is pretty large, which indicates that the dynamic α -factor of the QD device at the high photon density is significantly large, in contrast to the small "material" α -factor below the threshold. This is consistent with recent reports [14, 15];

the α -factor above the threshold shows that the linewidth enhancement factor increases with bias current. Several mechanisms have been suggested for the dependence of α on the light intensity.

The effective α depends on the photon number density due to the nonlinear gain suppression (increasing contribution of an excited-state transition to the optical gain due to intraband relaxation dynamics, carrier heating, and spectral hole burning) [16,17]. Quantum confinement affects the gain nonlinearity, and this nonlinearity causes enhancement of the linewidth enhancement factor with the increase of the photon density. The nonlinear gain coefficient of QD laser can be significantly larger than that of QW [18].

It should be noted that the concept of α becomes questionable when ultrashort optical pulses are involved. The usefulness and the limitations of the concept of the LEF were discussed in the transient regime, because α changes with both the carrier density and the optical intensity [19]. First-principle simulations of InGaAs QD lasers and amplifiers show that the α -factor is far from being a constant [20].

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CHAPTER 5: ULTRALOW NOISE OF QUANTUM-DOT MODE-LOCKED LASERS

5.1 Introduction

QD lasers are expected to show improved noise performance than QW/bulk due to their narrow linewidths. As discussed in section 2.2, the laser linewidth is proportional to

$$\Delta v \propto n_{sn}(1+\alpha^2)$$
,

where n_{sp} is the spontaneous emission factor. The multiple-QW lasers possess narrower linewidths compared to bulk lasers, and this is attributed mainly to the smaller n_{sp} in the multiple-QW lasers [1]. It was reported that the linewidth of a QD DFB is reduced by an order of magnitude than typical QW-DFBs [2].

Investigations have shown that QD-SOAs can exhibit superior noise characteristics as well as high gains and high powers, compared to other types of SOAs [3, 4]. Komori [5] predicted that in a quantum-dot SOA the signal-spontaneous beat noise is significantly reduced due to sharp gain characteristics and small n_{sp} . The small n_{sp} in the quantum dot structure can be explained by the high efficiency of population inversion and small waveguide loss; in other words, the carrier density is concentrated at the peak wavelength, and total carrier number required for amplification is much smaller that in the bulk structure [3]. The lower noise figure of QD-SOA has been verified experimentally [6].

These superior characteristics make it promising to use quantum-dot material as a gain element for laser operation. In this chapter, we demonstrate the superb performance of QD lasers in terms of noise properties. The inhomogeneous nature of QDs may reduce the modal relative

79

intensity noise (RIN) due to reduced competition between modes. The measurement of the modal RIN will be presented.

5.2 Noise of Mode-Locked Semiconductor Lasers

5.2.1 Noise of Mode-Locked Lasers

The mode-locked optical pulses fluctuate in amplitude and in arrival time, as shown in figure 5-1.



Fig.5 - 1: Amplitude fluctuation and timing jitter of mode-locked pulse trains.

The origins of noise of MLLs include spontaneous emission fluctuation, AM/PM noise of RF driving sources, environmental effects such as temperature or vibration, flicker noise of RF amplifiers, and supermode noise in HML. In addition, the detection and measurement process will add PIN photodiode noises, such as thermal and shot noise.

Since timing jitter is most critical in many high frequency applications, we will focus on the timing jitter of mode-locked lasers. The timing jitter is mainly driven by the spontaneous emission noise in the laser. A spontaneous emission causes timing jitter through fluctuations in the index of refraction, carrier density, and photon number; fluctuations in the index of refraction causes direct phase modulation, modifying the round trip time. Carrier density noise causes fluctuations in gain and pulse-position. The variation of photon numbers are correlated to gain fluctuations, and converts to timing fluctuations through AM to PM conversion [7].

In the following, we will show that the timing jitter is associated with the fluctuation of the linear phase component of correlated longitudinal modes. Under the mode-locking, the modes are coupled with each other, and their phases change collectively. Let us express the phase of *m*-th longitudinal modes, ϕ_m , as follows

$$\phi_m = \phi_0 + \phi_{m,0} + \phi_{m,1} + \phi_{m,2} + \dots$$

The ϕ_0 is a constant, which does nothing on physical quantity except in quantum optics. The $\phi_{m,0}$ is truly random, thus does not provide correlation between modes. The Schalow-Townes linewidth is determined by this component. However, timing jitter is not affected by this uncorrelated component. The $\phi_{m,1}$ describes a linear correlation between modes, that is, $\phi_{m,1} \propto m \varphi_1$, where φ_1 is a common value. The change of φ_1 in time will shift the position of pulses in time. From the observation, it is evident that the correlated linear phase fluctuation between modes will induce the timing noise. The $\phi_{m,2}$ (t) $\propto m^2 \varphi_2^2$ and higher orders describe quadratic and higher order chirp. For a detailed description, refer to [8]

When the linear correlation is dominant amongst the modes, the difference of the phase between two arbitrary modes spaced by N axial-mode intervals is $\Delta \phi = N \ \varphi_I$. As a result, when two-mode beating is considered, the phase noise spectral density will be proportional to $\sim N^2$ $\langle \varphi_I(t)^2 \rangle$. It shows that the phase noise increases as the spacing between two-modes increases, which is consistent with the analysis of [9] and the Linde's observation that the phase noise of Nth harmonic in spectral power density increases with N^2 [10]. In experiments, fluctuations of the pulse energy and timing in MLLs can be determined by the measurement of the noise power spectrum of the photodetector current [10-12]. The power spectrum is obtained from the electronic spectrum analyzer connected to fast photodetector outputs. The result of [11] is summarized here.

The laser intensity I(t) is a pulse train with an average power P, a pulse repetition period T, a normalized laser power fluctuation A(t), and a timing jitter described by the random variable J(t) for the pulse arrival time.

$$I(t) = PT[1+A(t)]\sum_{-\infty}^{\infty}\delta(t-nT-J(t)) .$$

Spectrum analyzer displays the power spectral density, $S_p(\omega)$, which is the Fourier transform of autocorrelation function,

$$S_{p}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \langle I(t)I(t+\tau) \rangle e^{i\omega\tau} d\tau$$

It follows then that

$$S_{P}(\omega) = P^{2} \sum \left[2\pi \delta(\omega - n\omega_{L}) + S_{A} \delta(\omega - n\omega_{L}) + n_{2} \omega_{L}^{2} S_{J} \delta(\omega - n\omega_{L}) \right],$$

to the first order in J(t), using the identity

$$\sum_{n=-\infty}^{\infty} \delta(t - nT - J(t)) = \frac{1}{T} \sum_{n=-\infty}^{\infty} \exp(jn\omega_L(t - J(t))),$$

where $\omega_L = 2\pi/T$. The $S_A(\omega)$ is the amplitude noise spectral density, and $S_J(\omega)$ is the phase noise spectral density. The actual spectrum displayed is given by

$$S_{M}(\omega) \propto |g(\omega)|^{2} S_{P}(\omega)$$
,

where $g(\omega)$ is the system response.

The rms amplitude fluctuation is given by

$$\sigma_A = \sqrt{\langle A(t)^2 \rangle} = \sqrt{\frac{1}{\pi} \int_0^\infty S_A(\omega) d\omega} \quad .$$

The rms jitter can be found by

$$\sigma_J = \sqrt{\langle J(t)^2 \rangle} = \sqrt{\frac{1}{\pi} \int_0^\infty S_J(\omega) d\omega}$$
.

5.2.2 Harmonic Mode Locking and Supermode Noise

When a modulator driving frequency is the same as the fundamental mode spacing (or the inverse of the round-trip cavity time), a single pulse circulates in the cavity, and it is called the fundamental mode locking. In our experiment of active mode-locking of a ring laser, a fiberized cavity is employed to increase the total cavity length (equivalently to increase cavity-*Q*). The driving frequency

$$f_m = N f_0$$

which is multiples of the cavity mode spacing, is applied to the modulator. There are *N*-pulses circulating in the cavity. This type of mode-locking is called harmonic mode locking (HML). The properties of HML are discussed in [13].

The sidebands produced by the modulator couple a given axial mode to its neighbors N axial-mode intervals away on each side. There are N-set of such coupled modes, which oscillate more or less independently, with the competition among them [14]. Each set consists of frequencies spaced N axial-mode intervals apart. The competition generates a new type of noise

called supermode noise, and can be observed in the RF spectrum. The details about noises and correlations in harmonic mode locking are described in [15].

5.2.3 Absolute and Residual Phase Noise Measurement

Direct detection of noise through the RF spectrum described in the previous section exposes several limitations; First, AM and PM noise are not separable. Second, the low noise level cannot be detected due to the finite dynamic range of the spectrum analyzer. Third, reliable measurements at 10 GHz or higher frequencies are not allowed due to limitations of the RF spectrum analyzer bandwidth.

In this section, we briefly provide an overview of the noise measurement based on phase detector methods [16]. There are two methods deployed in our study to measure the phase noise; the phase detector method and the delayed-line frequency discriminator method. The schematic of the phase detector method is shown in figure 5-2.



Fig.5 - 2: Phase detector method to measure the noise of a device under test (DUT).

A double-balanced mixer is used as a phase detector. This device serves to down-convert a primary carrier frequency to baseband (DC) by quadrature-mixing, followed by low-noise amplification of the sideband noise component. The removal of the carrier in this process greatly increases the effective dynamic range of the carrier-to-sideband noise measurement. The output is proportional to phase fluctuation. The single sideband noise power, L(f), is defined as the ratio of the single sideband power in a 1 Hz bandwidth to the total signal power, at a frequency offset f away from the carrier frequency. The noise level is normalized to a 1 Hz bandwidth. The L(f) is obtained from the RF spectrum data, S(f), through the proper calibration procedures.

Figure 5-3 shows the Absolute Phase Noise of E8247C synthesizer at 10.24 GHz. The Poseiodon's low phase noise oscillator was used as a reference oscillator. The noise output includes the phase noise of the driving source, as well as the noise of device under test (DUT). Often, the driving source is the predominant cause of the pulse train noise (i.e. the laser may not add a significant amount of extra phase noise). In this case the residual noise measurement is of more significance to understand the nature of fluctuations of the laser itself. The residual timing jitter is the timing jitter relative to a reference clock.



Fig.5 - 3: Absolute Phase Noise of E8247C synthesizer at 10.24 GHz. The synthesizer model has been extensively used as a RF driving source for this study.

The schematic of the residual phase noise measurement is shown in figure 5-4. The oscillator signal is split into two paths, one drives the DUT, anther goes to the LO port of the balanced mixer.



Fig.5 - 4: Residual phase noise measurement.

The RMS deviation of the residual timing jitter, Δt , is obtained from the power density in the PM noise sidebands, *L(f)*:

$$\Delta t = \frac{1}{2\pi f} \sqrt{2\int_{f_L}^{f_H} L(f)df}$$

5.3 Timing Jitter of QD Monolithic Mode-Locked Lasers

Owing to the potential of multi-section mode-locked lasers in practical applications, the phase noise of mode-locked two-section lasers has been extensively studied [17,18] in bulk/QW based lasers. Sub-picosecond (0.91 ps over the offset range of 30 kHz to 30 MHz) timing jitter was demonstrated from a 5 GHz monolithic passively mode-locked quantum dot laser [19], with a 7.8 mm long single chip device at 1250 nm wavelength.

In this section, we show the measurement of the phase noise of QD external cavity hybrid modelocked two-section lasers. Figure 5-5 shows the schematic of the setup. External cavity using a two-section mode-locked device and a mirror was built. The device (D3) was 2 mm long,

which includes a 250 µm long saturable absorber section. Strong chip modes are observed at 0 V reverse bias. The fundamental hybrid mode-locking at 10 GHz was achieved by RF power injection into the saturable absorber section. The lowest noise pulses were generated at 64 mA DC bias on gain section, and -9.3 V reverse bias and ~16 dBm RF injection on SA. The average output power ~0.6 mW from the oscillator was amplified through 4 mm long QD-SOA (4 deg tilt, uncoated).



Fig.5 - 5: Schematic of the setup. MLL: model-locked laser, M: mirror, OI: optical isolator.



Fig.5 - 6: (a) Optical spectrum, the inset shows the close-in optical spectrum showing combs with 10 GHz spacing, (b) autocorrelation.

Figure 5-6 shows the optical spectrum and the autocorrelation of modelocked pulse trains. The 3 dB spectral bandwidth was 3.5 nm, and the pulse width was 2 ps assuming sech² pulse shape. The time-bandwith-product (TBP) of 1.3 shows that the pulses were two times transfom-limited.

The residual phase noise was measured by the phase detector method using a double balanced mixer and a low noise base band amplifier (200 MHz bandwidth). Figure 5-7 displays the results of residual PM noise.

The phase noise is flat up to a corner frequency, about 250 kHz, and roll-offs ~20 dB/decade after it, which is a typical behavior observed from hybrid mode-locked semiconductor lasers. One surprising difference is that the authors in [20] obtained the corner frequency ~55 MHz from a 10 GHz QW-based two-section HML, which is two orders of magnitude larger than that of this QD laser. Another report on the phase noise of a QW HML laser [21] shows that the corner frequency is over 10 MHz.



Fig.5 - 7: Residual phase noise of 10 GHz hybrid mode-locked

two-section mode-locked laser.

The integrated timing jitter was 100 fs (100 Hz – 100 MHz), which shows significant reduction of jitter compared to that of QW MMLs. To confirm the generality, phase noise was measured with various devices and at different cavity lengths. The corner frequencies were measured typically below 1 MHz, consistent with the above result.

The coincidence between the residual phase noise corner frequency and the linewidth of longitudinal modes in a hybrid mode locked laser was investigated experimentally and supported by numerical simulation [22]. The direct relationship was observed in a theoretical modeling of passive mode-locked lasers [23]. With this observation, the average linewidth of longitudinal modes was measured by using the delayed self-homodyne technique [24], in which the Mach-Zender interferometer was employed, as shown in figure 5-8. A similar technique was used to measure the linewidth of a mode-locked semiconductor laser in [23]. The authors in [25] measured individual linewidths of a hybrid mode locked laser, and found that each longitudinal mode has the same linewidth.



Fig.5 - 8: delayed self-homodyne setup to measure to the average linewidth spectral combs of MLL, PC (polarization controller), OI (Optical isolator), DSO (Digital sampling oscilloscope), PD (photodetector).
A 1.5 km fiber was used to provide a long delay. The low-loss long fiber delay provides high resolution in linewidth measurements. A polarization controller is used to maximize the mixing signal power. The input is split into two paths, one of which is delayed through a long fiber delay, and then they are combined in a 3-dB fiber coupler.

The coherent time and coherent length of a MLL are given by

$$\tau_c = \frac{1}{\pi \Delta \nu}$$
$$L_c = c \tau_c$$

where Δv is the linewidth of a longitudinal mode. The delay length should be much larger than the coherent length.

To obtain efficient mixing, the pulses are required to overlap in temporal domain. The relative overlap is controlled by the adjustable optical delay. Figure 5-9 (a) shows the undelayed pulse trains and delayed replica before overlap, while figure 5-9 (b) shows the overlapped pulses. The intensity fluctuation due to coherence can be seen at the peak of overlapped pulses if the fiber delay is not long enough than the coherence length. Delayed pulses are broadened after passing through the long fiber. The average power of the two pulse trains was the same within 10% (0.1 mW before photodetector).



Fig.5 - 9: Sampling scope trace (a) before pulse overlap, (b) after overlap.

Figure 5-10 shows the RF spectrum of the photodetector current. From the 3dB bandwidth, the average linewidth of this laser was about 400 kHz, which approximately coincides with the corner frequency. This confirms that the origin of the reduced timing jitter of a QD MLL compared to QW MLLs is due to the narrower linewidth.

The authors in [2] measured the linewidth-power product of a QD-DFB laser of 1.2 MHz·mW in a device of 300 µm cavity length. They showed that the linewidth of the QD-DFB is an order of magnitude smaller than typical values of QW DFBs with the same cavity length.



Fig.5 - 10: RF spectrum of the photodetector current.

5.4 Modal RIN of a QD Mode-Locked Laser

Gain competition plays an important role in the laser dynamics in a homogeneously broadened laser. In mode-locked laser, multi-wavelengths share the same gain medium. Different modes will compete for the available population inversion in the laser. The gain competition has much stronger effects in homogeneously broadened lasers than in inhomogeneously broadened lasers.

The bulk/QW semiconductor lasers can be classified as a predominantly homogeneously broadened laser. On the other hand, the QD is inhomogeneously broadened gain medium due to rather separated QDs, thus mode competition in QD mode-locked lasers is expected to be smaller than in QW/bulk gain medium.

Figure 5-11 shows the setup of a grating coupled external cavity based on a two-section device. The 3 mm long device was used without any coating on the facets. By using a grating the number of modes is reduced, forcing the most energy to be concentrated on the small number of modes. The increased modal energy makes it easy to measure the RIN. The grating of 600 lines/mm was used.



Fig.5 - 11: Setup of a grating coupled external cavity based on a two-section device. QD SOA is used to amplify the output.

The mode spacing in this laser was 8 GHz, with a reverse bias of -6.3 V on SA. The output power of 0.6 mW was amplified with a SOA. The optical spectrum and the autocorrelation are shown in figure 5-12. The pulse width was 5 ps. There are 10 modes within 3 dB optical bandwidth of 0.39 nm. A TBP of 0.36 shows the pulses are close to transform limited.



Fig.5 - 12: (a) Optical spectrum, and (b) autocorrelation.

We built a filter using a diffraction grating (1200 lines/mm) to select out a single wavelength. Figure 5-13 shows a grating based filter design, consisting of a 2-inch grating, two achromatic lenses in a 4-f system. Achromatic lenses with a focal length of 500 mm were used to increase the F/# (minimizing spherical aberrations) and to increase the mode separation at the focal plane. The input beam is incident in a very shallow angle so that whole grating lines are used to maximize the resolution, which was estimated to be 0.021 nm (4 GHz) at 1270 nm. Two cylindrical lens pairs (focal lengths 80 mm,-20 mm and 300 mm,-60 mm, respectively) were used to make the beam size similar in horizontal and vertical planes at the detector coupling stage. Before coupling to detector/fiber, the beam size was about 6 mm by 8 mm. One convex and one concave lens were selected as a beam size expander and reducer. This combination effectively cancels the spherical aberration introduced by spherical/cylindrical surface, and reduces the beam distortion. This helped in increasing the coupling efficiency to the photodetector.



Fig.5 - 13: Grating-based optical filter. D – detector, OSC – oscilloscope, OSA – optical spectrum analyzer, RFSA – RF spectrum analyzer.

A slit was located in the focal plane of the 4-f system to pick up a single mode. The filtered optical spectrum is shown in figure 5-14. The resulting output was focused on the detector area and coupled into an OSA for wavelength monitoring. The Newfocus photodetector 1437 with 25 μ m X 25 μ m detector size, bandwidth 25 GHz, and responsivity of 0.12 A/W was used. The DC power coupled into the detector which was read from the photodetector and monitored through an oscilloscope.



Fig.5 - 14: Filtered optical spectrum.

Figure 5-14 shows the filtered optical spectrum of a longitudinal mode. The side modes were rejected by at least more than 10 dB. The RIN is defined as follows

$$RIN = \frac{\langle \delta P^2(t) \rangle}{\langle P \rangle^2} = \int_{-\infty}^{\infty} RIN(v) dv ,$$

where $\langle P \rangle$ is the average optical power, and δP is the fluctuation of the optical power. The true RIN value is obtained from the measured data by subtracting the shot noise, thermal noise contribution, and by taking account of the gain of the RF amplifier [26]. The shot noise is estimated from the average DC current detected with the fast photodetector. Figure 5-15 shows the RIN of a single longitudinal mode. The shot noise level at the input optical power was -142 dB/Hz, more than 10 dB below the measured RIN.



Fig.5 - 15: Measured modal-RIN.

The main noise source at high frequency offset is the intrinsic spontaneous emission of the mode-locked laser and the signal-spontaneous emission beating noise during the optical amplification. It is expected that the effect of inhomogeneously broadened gain medium on the gain competition may be observed in low frequency offset. However other low frequency noise sources, such as *1/f* noise of amplifiers or instability of external-cavity lasers, may make the measurement difficult. Further investigations are necessary.

5.5 Active Mode Locking of a Ring Laser

In this section, we investigate the noise performance of an actively mode-locked ring laser based on a QD SOA as a gain medium. A unidirectional ring laser is employed for low noise optical pulse generation in order to avoid the spatial hole burning detrimental to wavelength stability in the SOA [27].

5.5.1 Setup and Characteristics of the Laser

We constructed a linear and a unidirectional ring laser for comparison. Figure 5-16 shows the schematic of the linear cavity.



Fig.5 - 16: Linear optical cavity.

Continuous wave optical spectrum is shown in Figure 5-17 at different currents. The threshold current was 53 mA. It shows that in a linear cavity, longitudinal modes compete strongly with each other, leading to s multimode spectrum, except in a very small range of currents around the threshold.



Fig.5 - 17: Optical spectrum at (a) $I/I_{th}=1.02$ (54 mA), and (b) $I/I_{th}=1.22$ (65mA).

A unidirectional ring laser was constructed in free-space using a free-space optical isolator. The threshold of the system was 55 mA. Figure 5-18 shows the optical spectrum at 200 mA (I/I_{th} =3.6). The unidirectional ring laser is dominated by a single frequency even at high current densities, and more quite than the linear cavity due to the absence of the spatial hole burning. Unidirectional ring geometry removes this noise by only allowing a single unidirectional traveling wave to oscillate.



Fig.5 - 18: Optical spectrum at 200 mA (I/I_{th} =3.6) in a ring laser cavity.

It is evident that the unidirectional ring laser configuration will show much better performance for low noise pulse generation. Thus we built a unidirectional QD ring laser for active mode-locking using the QD SOA described above, a low loss Mach-Zender intensity modulator, an isolator, an output coupler, and polarization controllers.



Fig.5 - 19: Schematic of the unidirectional QD ring laser, QD-SOA, I: isolator, AM: Amplitude modulator, OC: 20% output coupler, PC: Polarization controller.

Figure 5-19 shows the schematic of the ring laser. The laser system is enclosed in a box made of a card board to shield the laser from air currents, improve temperature stability, and suppress acoustic vibrations. This simple insulation of the cavity from environment proved to be very effective. Enclosure with a hard and thick material such as acryl may improve it further. The cavity length was approximately 6 m corresponding to a fundamental cavity mode spacing of 25 MHz. The loss-modulated mode-locking is achieved by DC-biasing the SOA and applying the RF synthesizer (Agilent synthesized signal generator model 8247C) signal to the high-speed intensity modulator, driven at 12.8 GHz. Active mode-locking with low noise was well maintained over a broad range of DC bias conditions, ranging from 120 to 200 mA. Mode-

locking was optimized for the lowest noise operation at a DC bias of 170 mA on the QD-SOA, with an average output power of \sim 1 mW from the oscillator. The laser output was amplified through another QD-SOA to boost the optical power into the photodetector for further diagnosis. After amplification, the optical power was \sim 6.2 mW. Figure 5-20 shows the light output of the oscillator versus injection currents.



Fig.5 - 20: Light output of the oscillator versus injection currents.



Fig.5 - 21: Optical spectrum (a) logarithmic, (b) linear scale.

Figure 5-21 shows the optical spectrum of mode-locked pulses showing stable optical combs with more than 10dB comb contrast, limited by the resolution of the spectrum analyzer. The number of combs contained in the full-width at half-maximum (FWHM) bandwidth of 2 nm (370 GHz) is 29. The modulation of ~0.3 nm period imposed on the spectrum is due to the polarization crosstalk of the intensity modulator.

The mode-locked pulse trains were detected by a high-speed photodetector (50 GHz bandwidth), and are shown in figure 5-22 (a). The pulse width ranged from 24 to 28 ps in the low noise operating regime. The time-bandwidth-product (TBP) is ~10, implying that the pulses are highly chirped.



Fig.5 - 22: (a) mode-locked pulse trains, (b) RF spectrum.

5.5.2 Noise Measurements

The cavity length of fiberized ring lasers can be made long to increase cavity-Q due to longer photon storage time. The long cavity effectively narrows down the linewidth of longitudinal modes, resulting in reducing the noise. However, when harmonic mode-locking is performed, supermodes noises come into play. Figure 5-22 (b) shows the RF spectrum near the carrier frequency of 12.8 GHz. The supermode spurs at offset frequencies of multiples of the fundamental cavity frequency ~25 MHz are seen around the prominent carrier [28]. The supermode noise peaks are related to the beating between different supermodes whose center frequencies differ by multiples of the cavity round-trip frequency [15, 27].

The jitter level is critically dependent on the operating condition of the laser, in particular, detuning of the RF drive frequency from the cavity fundamental resonance frequency [17]. The effect of RF frequency detuning away from the minimum noise point on the supermode spur power is shown in figure 5-23. The supermode noise power level was less than -120 dBc/Hz, and was maintained over a 80 kHz detuning range. Beyond this range, the contrast in optical frequency combs is reduced, while the noise spur level increases dramatically, indicating that many longitudinal mode groups are involved in the mode-locking process.



Fig.5 - 23: Supermode level versus RF frequency detuning.

Figure 5-24 shows how optical and RF spectrum change with the RF frequency detuning. The center wavelength red-shifts at the positive frequency detuning (driving frequency is larger than the center frequency). The red-shift in the peak of the spectrum can be explained by selfphase modulation of the pulse as it passes through the laser chip [29]. The amount of the red shift of the spectral peak is proportional to the rate of carrier depletion. At large positive detunings, the pulses become unstable. The contrast of combs diminishes and supermode noises significantly increase. At large negative detunings much less spectral broadening occurs because the injection current always opposes the carrier depletion.



Fig.5 - 24: Optical and RF spectrum versus RF frequency detuning.

Figure 5-25 shows the phase noise of supermodes as a function of DC bias current. The noise decreases up to 170 mA. Above the current, the noise increases again, accompanying with broadening the optical spectral bandwidth. The phase noise is measured at the minimum noise operating condition.



Fig.5 - 25: Supermode noise level versus DC currents.

Figure 5-26 shows the single-sided phase noise L(f) and integrated timing jitter at the optimum condition, measured with the Agilent E5505 phase noise measurement system. Two distinctive features of this QD laser are noticed. First, substantially lower phase noise (>10 dB) is obtained at low-frequency offsets, as compared to QW-based lasers [10]. Second, the phase noise of the supermodes is suppressed down to -136 dBc/Hz. We note that this level of supermode noise has been obtained by employing high-finesse Fabry-Perot etalons inside laser cavities as a supermode suppression mechanism in QW-based mode-locked lasers [30, 31].



Fig.5 - 26: Residual phase noise and integrated timing jitter.

At low offset frequencies less than 10 kHz, the phase noise is predominantly 1/f. Although it stops at around 10 kHz, we believe the rolloff will continue all the way to the thermal noise floor. The spurious spikes at low frequency offset from 10 Hz-1 kHz are due to acoustic noise and vibration, line voltage fluctuations (60 Hz), and their harmonics picked up in the detection circuitry and data acquisition cables. The peaks are typically associated with mechanical vibrations. The white noise behavior beyond 5 MHz is considered primarily the signal-spontaneous beat noise owing to optical amplification, rather than the laser output itself.

The bump between 10 kHz and 1 MHz has been observed in both QW- and QD- based low noise lasers at the same position with a same synthesizer, where the position of the bump and noise level coincide with the phase noise specification of the Agilent RF synthesizer E8247. Our analysis shows that the bump is a result of incomplete cancellation of the synthesizer phase noise in the local oscillator (LO) and the RF port of the mixer used as a phase detector, due to a damping of the high frequency phase noise component in the laser. The utilization of a quieter oscillator as a mode-locking frequency source is expected to lower this bump level, and improve the measurement accuracy.

The spurious spikes at low frequency offset from 10 Hz-1 kHz are due to acoustic noise, vibration, line voltage fluctuations (60 Hz), and their harmonics picked up in the detection circuitry and data acquisition cables. The timing jitter calculated through

$$\Delta t = \frac{1}{2\pi f_{\text{mod}}} \sqrt{2 \int_{f_{\text{min}}}^{f_{\text{max}}} L(f) df} \quad ,$$

gives ~7.5 fs (7.5 fs/78 ps~0.01% relative timing jitter) integrating from 1 Hz to 10 MHz, which is the lowest residual timing jitter reported from an actively mode-locked semiconductor laser. This result shows that quantum-dot mode-locked lasers are promising as sources for ultralownoise optical pulse trains. It is also comparable to the residual timing jitter of a mode-locked fiber laser (~6.9 fs) [32], or even better when the bump is neglected, at the same carrier frequency.



Fig.5 - 27: AM noise of actively modelocked ring laser at 12.7 GHz

The preliminary AM noise is measured by using the same noise measurement system, shown in figure 5-27. The AM noise is slightly higher than PM noise.

5.6 Effects of Chip Modes on Active Mode Locking Performance

Harmonic mode-locking leads to the supermode noise. Several techniques have been used to suppress the supermode noise. One of the effective methods to suppress the supermode noise is to use an intracavity Fabry–Pérot (FP) etalon which increases correlation among circulating pulses by imparting the energy of one pulse to following pulses [Chr02]. In other words, in frequency domain, the etalon filters out most cavity modes except the etalon modes. The ring laser with the etalon is shown in figure 5-28



Fig.5 - 28: Ring laser with an intracavity Fabry-Pérot (FP) etalon to suppress supermode noise.

In this setup, high finesse etalons, F=70-300, are typically used for effective supermode suppression. A high effective finesse can be achieved without using high finesse etalons. When the gain medium is placed between two external mirrors of low reflectivity, the reflected light from the mirrors is amplified by the optical gain. An external linear cavity was built based on a QW-SOA to test this idea. Two partial mirrors with reflectivities of 10 % were positioned in both sides of the SOA, as shown in figure 5-29. Although the low reflectivity mirrors form a low finesse etalon (F~1.1), a high effective finesse is high due to the gain medium between the mirrors.



Fig.5 - 29: Harmonic modelocked linear cavity.

The mode-locking frequency was about 1 GHz, with 4-th harmonic mode-locking. The RF spectrum in figure 5-30 shows the supermode suppression as a result of the high effective finesse of the configuration. Supermode noises are clearly reduced, but the noise sideband close to the carrier seems to increase.



Fig.5 - 30: RF spectrum of mode-locked pulses of the linear cavity laser

(a) without mirrors, (b) with mirrors.

By taking advantage of long device length of QD-SOAs, the idea can be further explored in high frequency mode-lockings. QD-SOAs with different waveguide angles were fabricated. The residual reflection of the uncoated facet was used as a mirror mechanism, as shown in figure 5-31



Fig.5 - 31: Ring laser cavity with facets as partial mirrors.

The length of the QD-SOA was about 4 mm, corresponding to 10 GHz. Active modelocking was achieved by driving the intensity modulator at the same frequency. Figure 5-32 shows the phase noise of the ring laser with waveguide angle 2 degree, at two DC currents, while figure 5-33 with waveguide angle 3 degree. The supermode noise spur is not suppressed in this laser.



Fig.5 - 32: Phase noise of the ring laser, waveguide angle 2 degree, (a) 88 mA, (b) 110 mA



Fig.5 - 33: Phase noise of the ring laser, waveguide angle 3 degree, (a) 110 mA, (b) 150 mA

The phase noise level of the 2nd super mode (which is approximately equal to the noise level of the plateau region) for different waveguide angles were compiled in figure 5-34. The data shows a clear tendency; the phase noise is high in 2 and 3 degree angles. Due to the small waveguide angle, the SOAs lase by themselves at low DC currents. When the DC current is about the threshold current of the SOA itself, the noise level abruptly increases.



Fig.5 - 34: (a) Supermode phase noise level of the ring laseras a function of DC current for devices with different waveguide angles,(b) DC current is normalized to the threshold current of the Ring Cavity.

In the FP lasers, counter-propagating beams make a standing wave inside the device which produces nonuniform carrier (or gain) distribution. Other longitudinal modes can obtain enough gain to undergo laser oscillation. This causes multi-longitudinal mode operation with significant competition between the modes. [33]. Thus the increase of phase noise around the device threshold, observed in figure 5-34, is understood as a result of the spatial hole burning.

In quantum well or bulk lasers, diffusion in the active region will tend to smooth out the nonuniform carrier distribution and population inversion along the longitudinal direction, thus suppressing the effect of the spatial hole burning. In QD, diffusion will play a similar yet minor role [34]. Thus it is expected that the spatial hole burning plays a more significant role in the QD lasers.

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CHAPTER 6: QUANTUM-DOT LASER BASED OPTO-ELECTRONIC-OSCILLATOR

<u>6.1 Introduction</u>

Microwave oscillators providing reference clock signals are the key elements in modern communication systems. Most widely used resonators are made of crystal quartz. However it cannot generate high-frequency signals directly, since quartz has only high-Q resonant modes at low frequencies. A high frequency RF/microwave signals are generated by multiplying a lowfrequency reference with several stages of multipliers and amplifiers. In this case the phase noise increases quadratically with frequency. In addition, the systems are bulky, complicated, and costly.

Up to date the lowest phase noise oscillators at microwave frequencies have been achieved by utilizing sapphire whispering gallery mode resonators providing high-Q at high frequencies, combined with noise detection and reduction circuitry based on the Carrier Suppression Interferometer [1-3].

Opto-electronic oscillator (OEO) is a new class of oscillator. The photonic oscillator converts a continuous light energy into stable and spectrally pure RF/microwave signals [4,5]. It provides spectrally pure signals, with both electrical and optical outputs. The idea of the regenerative RF feedback is an old concept [6-8]. The key elements in the OEO are a long fiber delay and narrow band pass filter (BPF).

In AML and HML, achieving the ultimate low-noise performance requires the use of a low noise oscillator or a synthesizer as a driving source. One can combine the OEO and the

115

mode-locked laser into a single coupled OEO (COEO) [9] to simultaneously generate the high purity electrical sinusoidal signal and low noise mode-locked optical pulses without using a separate driving source. Another advantage of using the regenerative feedback is to get rid of the external oscillator.

In this chapter, the OEO and the COEO are demonstrated. Since QD lasers shows low noise performance, they are possible candidates for low-noise COEO-type pulse sources. The phase noise of the COEO is measured by the photonic delay line frequency discriminator method. The COEO using a monolithic device is also demonstrated.

6.2 Opto-Electronic Oscillator (OEO) as a Ultralow Phase Noise Microwave Signal Source



Fig.6 - 1: Schematic of OEO.

Figure 6-1 shows the schematic of an OEO [4]. The laser output is introduced into an electro-optical modulator, then it passes through a long optical fiber and detected with a photodetector. The output of the photodetector is amplified and fed back to the modulator. The oscillation starts from noise transients, which are then built up and sustained with feedback, at a frequency determined by the fiber delay length, the filter bandwidth, and the bias of the

modulator. The oscillation sustains when the loop gain exceeds the loss for the oscillation modes. The mode spacing of the OEO cavity is inversely proportional to the fiber length. The RF bandpass filter is used to select a single mode or a set of modes (Figure 6-2).



Fig.6 - 2: Oscillation modes of the OEO loop. The τ_d is the delay time of the loop.

The phase noise of an oscillator is determined by the Q value of its resonator. The key to low-phase noise and high spectral purity is the long fiber delay, which allows for a large Q with very little loss of about 0.3 dB/km at 1.3 μ m. The quality factor of the loop delay line is given by

$$Q_D = 2\pi f_{osc} \tau_d ,$$

where τ_d is the delay time and f_{osc} is the resonant frequency. A 1 km fiber has a Q_D of $3 \cdot 10^5$ at 10 GHz.

We implemented the low frequency (640MHz) OEO in the following (figure 6-3). The tunable laser HP 8168F or DFB laser was used as a CW laser source. The OEO using the DFB laser was found to be more stable. Here a high-*Q* narrow bandpass filter of K&L Microwave Inc., C40, with band width=0.2%, 6 section cavity-type filter was used. The loss of the BPF was measured to be about 13 dB.



Fig.6 - 3: OEO based on a tunable laser source. The center frequency is 640 MHz.





Fig.6 - 4: Sinusoidal RF tone generated from the OEO.

The length of additional fiber is (a) no additional fiber, (b) 100 m, and (c) 1 km. The span is 50 kHz in all cases.

Figure 6-4 shows how sinusoidal RF tones generated from the OEO improve with different fiber lengths. By the use of 1 km fiber, the spectral purity significantly improves. A serious problem of the use of a long delay is the multimode operation; due to the narrow mode spacing, several modes can oscillate within the bandwidth of the RF bandpass filter.



Fig.6 - 5: Multimode oscillation at higher loop gain, EDFA pumping current of (a) 180 mA, (b) 200 mA.

Figure 6-5 (b) shows equally spaced multiple oscillation peaks, which is a major problem of OEOs. The RF filter is not able to filter out many of the unwanted modes, especially those close to the carrier. A few solutions have been suggested, such as injection locking [10] and the use of multi-loops [11], although they increase the complexity and the size of OEOs.

6.3 Coupled Opto-Electronic Oscillator (COEO)

Mode-locked laser oscillators can be combined with the OEO [9]. The intensity modulation inside the loop forces the laser into actively mode-locked operation. The RF/microwave loop takes the electronic signal from the beat notes of the mode-locked laser. The signal is filtered, amplified, and fed back into the AM modulator. One of the laser mode beat frequencies is required to coincide with one of the OEO modes. The two feedback loops form a coupled pair of oscillator. Figure 6-6 shows the setup of the COEO. The RF loop consists of a phase shifter, a RF bandpass filter (BW=0.1 % of the center frequency, K&L C60, 6 section.) centered at 10.24 GHz for mode selection, and RF amplifiers. The RF filter introduces 6.7 dB of loss. The variable attenuator allows us to control the amount of loop gain. A low-noise high-gain amplifier provides the first 40 dB of gain. A high-power amplifier provides the rest of the required gain and delivers the 22 dBm signal to the RF modulation port.



Fig.6 - 6: Setup of COEO.

Figure 6-7 shows that the microwave tone generated from the COEO is clean without adding an additional fiber to the OEO loop. When 1 km delay fiber (~5 us delay) was used, the modes were spaced 200 kHz apart. About 5 modes are within the filter bandwidth. The phase was adjusted to make a laser beat note coincide with a mode of the OEO loop.



Fig.6 - 7: RF/microwave tone without additional fiber in the RF/microwave loop with span of (a) 50 MHz, and (b) 20 kHz.

6.4 Absolute Phase Noise Measurement by sing Photonic Delay Line Method

Since the phase noise of the photonic oscillators is lower than commercial oscillators that we have, the photonic delay line homodyne technique was used to measure the absolute phase noise, shown in figure 6-8 [12,13] (the dual-channel cross-correlation scheme can be used together to lower the noise measurement floor [14]). The phase difference at the mixer output is proportional to input frequency fluctuations. Unlike the phase detector method, the frequency discriminator method does not require a second reference source phase locked to the source under test.



Fig.6 - 8: Delay line frequency discriminator method.

The pulse trains are split into two paths in the photonic delay line method, as shown in figure 6-9. A bandpass filter can be inserted after the photodetector to select a harmonic frequency.



Fig.6 - 9: Photonic delay line method for measurement of the absolute phase noise using a low loss fiber delay.

Figure 6-10 shows the actual implementation of the delay line method for the absolute phase noise measurement of the COEO, where the OEO loop is a part of measurement system..



Fig.6 - 10: Setup for the absolute phase noise measurement using the frequency discriminator method.

The microwave output of ~ 17 dBm is tapped directly from the output of the amplifier as an input to the local oscillator (LO) port of the mixer. Figure 5-8 shows the phase noise of the

COEO. The oscillator phase noise spectral density shows a $1/f^2$ (20 dB/decade) behavior (in the entire range). It reaches below -110 dBc/Hz at 10 kHz. The measured noise is compared to the noise of a high-performance synthesizer (HP83712B), as shown in figure 6-11. It is evident that at 10 kHz offset from the carrier, the phase noise of the COEO is more than 10 dB better than that of HP83712B.



Fig.6 - 11: Absolute phase noise of the COEO and comparison with HP83712B synthesizer.

The mode-locked laser in the photonic oscillator serves as a high-Q filter. The high Q originates from the high regenerative gain of the mode-locked laser. In a COEO configuration based on an EDFA which consists of a 150 m long mode-locked laser loop and a 2 m long RF loop, a 9.2 GHz signal with less than -140 dBc/Hz phase noise at the 10 kHz offset frequency was demonstrated [15] without using an additional delay fiber.

The sources of noise in COEO include amplifier flicker noise, thermal noise, the shot noise, and laser's intensity and phase noise. The Leeson model describes the phase noise behavior of oscillators, and allows the prediction of the oscillator noise performance on the basis of the measured noise of each component [16-19]. According to the model, the L(f) of an oscillator is given by

$$L(f) = \left[1 + \left(\frac{f_L}{f}\right)^2\right] \frac{S_{\varphi}(f)}{2}$$

where $S_{\varphi}(f)$ is the total phase noise spectral density of the loop, Q is the effective quality factor of the resonator (mode-locked laser in this case), and

$$f_L = \frac{v_0}{2Q}$$

is called the Leeson frequency. The above equation indicates that below the Leeson frequency, the oscillator phase noise catches up an additional $1/f^2$ factor from the loop phase noise [19]. In general an RF amplifier's noise consists of flicker noise (~1/f) and white noise, as shown in figure 6-12. The white noise level depends on the input power to the amplifier. If the mode-locked laser oscillator is not the dominant source of noise in this COEO, the origin of $1/f^2$ in the phase noise of the COEO might be due to the power-dependent white noise floor of high gain amplifier chains in our system. The low optical output power from the laser requires a high RF gain in the OEO loop, and the white noise may limit the noise performance of the oscillator.



Fig.6 - 12: Typical phase noise behavior of RF amplifiers; it consists of flicker noise (~1/f) and white noise. The data is the phase noise of a Miteq amplifier at10 GHz.

6.5 Regenerative Mode Locking Based on Passive Mode-Locked Two-section Devices

The timing jitter of passive mode-locked clock signals can be greatly reduced either by applying an external oscillator signal or by the regenerative feedback of the laser output the same way as in the previous section. Figure 6-13 shows the COEO using a monolithic mode-locked laser.

The cavity frequency was set to 4.3 GHz. The length of fiber was 500 m fiber. The noise level was significantly reduced in both COEO and HML, shown in figure 6-14. However the modulation with ~300 kHz period due to the 500 m fiber delay was unavoidable in the COEO.


Fig.6 - 13: COEO using the monolithic mode-locked laser.



Fig.6 - 14: RF spectrum of pulse trains. dash-dot-dash, PML, dash-dash COEO, and straight line, hybrid ML. Both COEO and HML greatly reduce the noise level. The modulation period of ~300 kHz corresponds to the mode spacing of the OEO loop, 500 m fiber delay.

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CHAPTER 7: SUMMARY AND FUTURE WORKS

7.1 Summary

This dissertation explored the potential of QD mode-locked lasers toward a goal to reach high speed, ultrashort, high power, and ultralow noise pulse sources. The main achievements of this dissertation are; successful design and fabrication of various devices, such as QD FP lasers, QD SOA, and monolithic two-section devices; achievement of high peak power subpicosecond pulse width; and demonstration of significantly improved noise performance of QD mode-locked lasers compared to QW/bulk lasers. More detail follows.

Based on the waveguide study for single mode operation and suppression of residual reflectivity, we designed various QD devices, such as FP laser, SOA, and monolithic two-section devices. The fundamental characteristics were investigated. Internal loss was 1.1 /cm, showing the device length can be long as 1 cm. The LEF was measured to be near zero below threshold current. High gain of 19 dB and saturation output power of 15 dBm were achieved from the SOA.

A master-oscillator power-amplifier (MOPA) system using a monolithic two-section device and QD-SOA was built. Subpicosecond (960 fs) pulses were achieved after compression using a dispersion compensator. The peak power of 1.2 W was obtained, which was the highest peak power from QD mode-locked lasers at the time of this experiment [1]. Although the subthreshold α -factor was small, the effective α was bigger than predicted. The dependence of the effective α on the photon density was understood as a result of the increased nonlinear gain compression factor in QD media. The residual timing jitter of ~ 100 fs (100 – 100 MHz) was achieved from the HML QD monolithic laser. A home-built noise measurement box was used for the measurement. This significant reduction of timing jitter with compactness, simplicity, and low cost of QD semiconductor lasers, may lead to practical sources for optical clocks in interconnect application.

As a purpose to increase the cavity Q, a unidirectional fiberized actively mode-locked QD ring laser with a cavity length 25 MHz was investigated. The residual timing jitter of 7.5 fs (1 Hz – 10 MHz) was achieved. Supermode phase noise level was found to be suppressed down to -136 dBc/Hz. These numbers represents an order of magnitude improvement of the noise performance in QD MLLs [2].

Finally we demonstrated a CW-laser based OEO and a mode-locked laser based COEO. From the absolute phase noise measurement and model based analysis, the white noise of RF amplifiers was found to play a dominant role in the low frequency phase noise. Higher optical output power with the proper use of RF gain and low phase noise amplifiers is essential in reducing the noise level.

7.2 High Power QD lasers

QD gain media have a potential as high energy devices with improved beam quality and temperature insensitivity; low internal loss implies the higher electric-optical energy conversion efficiency. Heat removal is more efficient due to its long device length, as compared to conventional devices with shorter lengths. High saturation power of QD SOAs was also demonstrated [3].

The output saturation energy of laser gain medium is given by

130

where hv is the photon energy, A is the area of the active region, and dg/dn is the differential gain. Devices with wide waveguide widths should deliver higher output energy.

A simple approach to achieve higher power is to use a broad area SOA to amplify the input power generated from the master oscillator. Tapered amplifiers are an effective approach to increase the output power while keeping good beam quality. They consist of a preamplifier and a tapered section, shown in figure 7-1. The preamplifier section is realized as a ridge-waveguide structure, and should have a length of several 100 μ m in order to provide preamplification and mode selection [4]. An absorber is necessary to suppress parasitical lateral lasing.



Fig.7 - 1: Schematic of tapered amplifier, (a) straight preamplifier requires very good AR coating to prevent lasing, (b) preamplifier section is curved.

The angle of the tapered section should coincide with the diffraction angle of the propagating Gaussian beam, which is 6° for the mode field diameter of 5 µm. The axial dependence of the power in the tapered amplifier is governed by [5]

$$\frac{dP}{dz} = \left(\frac{g_0}{1 + \frac{P}{A(z)I_s}} - \alpha\right)P$$

where the effective-saturation power $A(z) \cdot I_s$ increases with increasing z.

The beam propagation method (BPM) simulation of a tapered amplifier is shown in figure 7-2. The preamplifier section is a 400 μ m long and 4 μ m wide ridge-waveguide.



Fig.7 - 2: BPM simulation of a tapered amplifier.

Another approach to achieve high power from QD lasers has been demonstrated in [6]. The authors fabricated deep-etched ridge stripe lasers without surface recombination at open side walls. One important characteristic to note is that single transverse mode was maintained at high driving currents, although the waveguide width was about 8 μ m. Owing to the wide beam size, high output power was obtained. We designed SOAs and two-section devices with a similar structure, shown in figure 7-3.



Fig.7 - 3: Waveguide structure of deep-etched SOAs and two-section devices

for high output power.

This waveguide is index guided structure, which will have the lowest excess noise factor, K=1. As a result, it is expected that noise performance will also be improved.

7.3 Dispersion Managed Mode-Locked Laser using Waveguide Saturable Absorbers

An intrinsic problem of monolithic two-section devices is that the SA section shortens pulse width, while gain section stretches pulse width. Since the two mechanisms are not compatible, achievable pulse width and peak power are limited in these devices.

Resan et al [7] studied a dispersion managed mode-locked laser. They used a multiple quantum well wafer as a SA in which excitonic absorption provides the saturable absorption mechanism. The pulses were stretched before entering the semiconductor gain medium to minimize the detrimental self-phase modulation and to enable efficient pulse amplification. Subsequently compressed pulses facilitate bleaching the semiconductor saturable absorber. The authors could achieve 185 fs pulse width and 230 W peak power in 850 nm wavelength. The excitonic absorption type SAs have not been demonstrated yet in longer wavelengths other than 850 nm and 980 nm.

The length of a saturable absorber in a QD monolithic mode-locked laser is typically 200 μ m – 300 μ m, which makes it possible to physically separate the SA from the gain section. The schematic of a dispersion managed mode-locked laser using the separate waveguides is shown in figure 7-4, which is similar to the cavity used in [7].



Fig.7 - 4: Schematic of a dispersion managed mode-locked laser using a waveguide saturable absorber and gain separately.

7.4 Tunnel Injection Laser

In QD media, the gain recovery time is measured to be in the sub-picosecond range for both ground (150 fs) and excited state transitions (180 fs) [8]. This ultrafast gain recovery dynamics allows ultrafast devices. However, when pulses are injected at high repetition rates, the response can be significantly affected by the slower recovery time of a few picoseconds in the excited state and the wetting layer transition (phonon bottleneck problem) [9]. This problem can be solved by using tunnel injection lasers [10] and p-doped lasers [11]. The new structures are expected to significantly improve device performances by reducing the hot carrier effects and the effect of the nonlinear gain suppression due to the slow relaxation time between ground and excited states.

7.5 Conclusion

Significant performance enhancements were achieved from QD mode-locked lasers. As future works, we proposed high power laser systems based on a deep-etched wide waveguide device, tapered amplifiers. The dispersion managed mode-locked laser using a waveguide SA will lead to higher peak power and shorter pulses. QD mode-locked lasers based on the tunneling injection structure may further improve the performance of the lasers.

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