Quantum dot based mode locked lasers: performance and applications

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***Abstract*-Recent progress in semiconductor quantum dot based mode locked lasers is discussed. Sub-picosecond pulse generation and extremely low phase noise have been demonstrated for both InAs/GaAs and InAs/InP material systems. Applications include e.g. OTDM sources and frequency comb generation for WDM systems, all-optical clock recovery at high bit rate or microwave photonics .**

Keywords- self-assembled quantum dots; semiconductor mode locked lasers; pulse generation; phase noise; fiber optic telecommunications; microwave photonics

I. INTRODUCTION

Self-assembled semiconductor quantum dot (QD)-based lasers are attracting considerable interest owing to their predicted remarkable properties that result from the three-dimensional carrier confinement. Extremely low threshold currents [1] as well as high temperature stability have readily been demonstrated in the InAs/GaAs material system together with temperature independent transmission experiments at 10 Gbit/s [2].

Monolithic mode locked laser (MLLs) diodes are very attractive short pulse sources for a number of applications including Optical Time Division Multiplexing (OTDM), all-optical clock recovery, microwave photonics,…[3]. III-V QD-based active layers have recently been used in the fabrication of MLLs. Inhomogeneous broadening of the gain spectrum due to QD size distribution is indeed an asset for MLLs as this should result in pulsewidth reduction. Ultra-fast carrier dynamics is also a major advantage in the short pulse generation. Finally the low optical confinement factor leads to very small phase noise and this results in low timing jitter as compared to the quantum well based MLLs.

II. SHORT PULSE GENERATION AT HIGH REPETITION RATE

Early demonstration of a monolithic passively mode locked laser using QD based active layer was reported at ~1.3 µm using InAs/GaAs QDs [4]. 17ps wide pulses were generated at a repetition rate of 7.4 GHz, both values being limited by the available optical modal gain in a two-QD layer stack. Advances in Molecular Beam Epitaxy (MBE) material growth allowed to stack several QD layers thus enabling mode-locking with much improved performance in terms of pulse width, repetition rate, noise properties,...

A recent review summarizes the main achievements in this field [5]. Sub-picosecond pulse durations were readily demonstrated by several groups using InAs/GaAs QDs, without resorting to pulse compression schemes [6-8]. This was made possible owing to the wide inhomogeneously broadened optical gain spectrum as well as extremely fast absorption recovery under reverse bias in the saturable absorber section of the devices. Increased peak powers were also reported as mode locking occured in a large range of injection currents above threshold.

Many applications require high repetition rates which are given by the inverse of the round trip cavity time. High modal gain active layers are hence necessary to achieve the highest repetition rates corresponding to the shortest laser cavities. Enhancement of the optical gain using 15 QD layers allowed a record repetition rate of 80 GHz to be achieved associated with a 1.9 ps pulsewidth obtained from a 0.5 mm long passive mode locked laser based on InAs/GaAs [8].

MBE growth of InAs quantum dots on InP (100) substrates generally leads to the formation of quantum " dash " nanostructures (elongated dots). These nanostructures however exhibit very interesting properties pertaining to short pulse generation using mode-locked lasers. They in particular provide a higher optical gain compared to that of QDs grown on GaAs susbstrates [9]. Sub-picosecond pulse generation was reported at a very high repetition rate of 134 GHz [10]. Of particular interest, these results were achieved using a single section self-pulsating Fabry–Perot laser, i.e. without resorting to an absorber section. In this latter configuration, enhanced four-wave mixing (FWM) is invoked as the driving mechanism of the passive mode locking which induces a strong correlation between the longitudinal modes. Similar results were reported for InAs QDs grown by Chemical Beam Epitaxy (CBE) on InP [11]. Other investigations used Metal Organic Vapour Phase Epitaxy (MOVPE) for the growth of InAs QDs on InP [12].

Further growth optimization of quantum dash (QDash) nanostructures allowed laser emission for very short cavities down to ~120 µm, which resulted in the generation of sub-picosecond pulses with a record high repetition rate of 346 GHz [13].

III. NOISE PROPERTIES OF QD MLLs AND APPLICATIONS

QD-based mode locked lasers have shown very interesting noise properties related to the expected low n_{sp} noise factor and to the small coupling of the amplified spontaneous emission (ASE) to the optical mode owing to the relatively small optical confinement in these material systems.

They have demonstrated very narrow radio-frequency (RF) linewidths, ~two orders of magnitude less than those of quantum well MLLs [10, 14]. A record low RF linewidth of 500 Hz has recently been reported for a 10 GHz passively mode locked InAs/GaAs device [15]. Phase-noise measurements on the same device yielded an integrated timing jitter of 147 fs (4 MHz to 80 MHZ) for passive and 197 fs (20 kHz to 80 MHz) for hybrid mode-locking.

The effect of optical feedback on the noise properties of a InAs/InPQDash based laser has been investigated in [16], with the demonstration again of a 500 Hz RF linewidth, which indicates low phase noise and hence low 'high frequency' timing jitter.

These monolithic mode locked lasers are hence promising sources for many applications that require high repetition rates, low timing jitter, narrow RF linewidths such as high bit rate optical communications, millimeter wave signal generation, or optical sampling [17].

All-optical clock recovery, based on the optical injection locking of a QDash based MLL, has been performed at 40 Gbit/s, compliant with ITU-T recommendation [18]. The one-section self-pulsating QDash laser realizes high-frequency jitter suppression owing to its inherently narrow free-running RF spectral linewidth. This result paves the way to all-optical clock recovery up to 160 Gbit/s.

The wide optical spectrum (~10 nm) of mode locked QDash lasers has recently been exploited in WDM comb generation consisting of 100 GHz –spaced channels [19]. Separate error-free transmission of eight channels was successfully performed at 10 Gbit/s.

The very narrow RF linewidth makes QD MLLs very attractive for high frequency signal generation for radio transmission or radar applications. They have been successfully implemented for the generation of 60 GHz carriers for wireless transmission of high speed data streams [20]. It has also allowed significant phase noise reduction in millimeter-wave coupled opto-electronic oscillators [21].

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