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Comb Line Generation Using Gain Flattened Ring Mode Locked Laser

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Abstract— ***we briefly demonstrate combinational line generation from an integrated multiple quantum well in GaAs/InP passively mode-locked laser (MLL) with a gain flattening filter based on an mach-zehnder interferometer. The intracavity filter flattens the non-uniform gain profile of the semiconductor material providing a more uniform net cavity gain. The GFF MLL has a gain of -10dB comb span of 15nm (1.88THz), the widest spectral width yet demonstrated for an integrated qw MLL at 1.55(micro meters). The measured optical linewidth at the center of the comb is 29 MHz, the -20dB RF gain line width of 500 KHz, while the output spectrum is phase-locked to produce 900 fs pulses at a repetition rate of 30 GHz with 4.6 (pico second) integrated jitter from 100Hertz to 30 (MegaHz)***

Index Terms- comb-line generation, integrated optics, mode-locked lasers, optical communications, photonics integrated circuits.

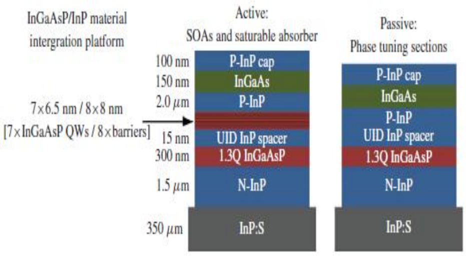
I. INTRODUCTION

Integrated In GaAsP/InP mode-locked lasers (MLLs) Operating at 1.55 μm wavelength are very stable pulse sources that can be used in a variety of applications in high speed optical communication such as optical time domain multiplexing and optical sampling. Since a single MLL generates multiple phase-locked lasing modes that coherently add up to form the short pulses, MLLs can also be used for frequency comb-line generation (i.e. a multiwavelength source [1]) in applications including offset frequency locking [2], and light detection and ranging (LIDAR). For wavelength-division-multiplexing (WDM) applications, a broadband phase-locked comb of frequencies can be used for rejection of cross-talk to allow more closely spaced non-return to- zero (NRZ) channels and a higher spectral density [3]. In coherent communication systems, such frequency combs can greatly reduce the required front- and back-end footprint and overhead for laser stabilization and carrier tracking [4]. For example, a frequency comb that spans 1 THz can provide 40 WDM channels, each having a bandwidth of 25 GHz and has a substantially smaller footprint than 40 single tone lasers. Furthermore, a single wavelength locker can provide stabilization for all of the comb's periodic frequency lines. A homodyne coherent receiver would typically require each channel to have its own local oscillator (LO) for carrier synchronization [5], [6] (e.g. 40 lasers and 40 optical phase locked loops (OPLLs)).

However, a single phase-locked comb with an OPLL can supply all necessary LOs for the incoming signals. Since all lasing lines are phase-locked and have fixed frequency spacing, this effectively locks all channels. In a semiconductor MLL, the span of the comb is determined by the cavity dispersion and the gain competition between its various lasing modes. While the semiconductor medium can generate gain that spans over 100 nm, the gain competition arising from the nonuniform material gain as a function of wavelength limits the bandwidth of the resulting frequency comb. By applying an intracavity filter function as an inverse of the spectral shape of the material gain, the resulting gain flattening creates a more uniform spectral profile. This allows for wider combs as demonstrated with bench-top MLLs [7]. Previously, we have shown the generation of 600 fs pulses from a monolithically integrated 30 GHz MLL with an intracavity gain-flattening filter (GFF) [8]. Additionally, we have compared the frequency comb span of the GFF MLL to standard MLL designs on the same material platform and have shown an improvement >2x [9]. In this letter, we present optical linewidth, RF linewidth, single sideband phase noise measurements, and a −10 dB comb span of 15 nm (1.88 THz). This is the widest frequency comb generated from an integrated quantum well (QW) based MLL at 1.55 μm, with a span matching state-of-the art quantum-dot (QD) and quantum-dash MLLs [10]. Moreover, such GFFs can be used to improve the gain flatness on any material platform, including: QDs, QWs, and bulk.

II. RING MILL FABRICATION

We have chosen ring-based mode-locked laser architecture Due to its ease of integration with other components to realize Highly versatile photonic integrated circuits (PICs). These Rings and their couplers can be defined using low-cost and High throughput i-line photolithography, allowing ring MLLs To be placed anywhere on the PIC without the need for more Complicated processing. Thus rings can overcome fabrication Complexity faced by distributed Bragg reflector (DBR) and Distributed feedback lasers (DFB) that require gratings defined.



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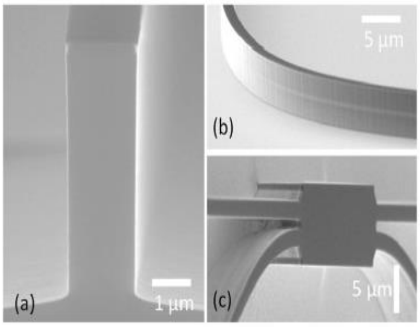


Fig. 2. Scanning electron microscope (SEM) images of the etched waveguide showing (a) 5 μm deep etch with vertical sidewalls, (b) waveguide bends with smooth sidewalls, and (c) multimode interference (MMI) couplers.

By holography or electron-beam-lithography, this can be expensive with reduced yield. A ring MLL with a GFF is designed and fabricated onan InGaAsP/InP offset quantum well (OQW) platform that consists of seven 0.9% compressively strained 6.5 nm QWs and eight −0.2% tensile strained 8 nm barriers that are epitaxial grown above a 300 nm thick 1.3Q InGaAsP layer as part of the base epi. Passive areas are defined using a selective wet-etch and a single blanket regrowth is done to cover the device with a p+-doped InP cladding, a p++-doped InGaAs contact layer, and an InP capping layer to protect the InGaAs contact layer during device fabrication. The active material is used to define the semiconductor optical amplifiers (SOAs) and the saturable absorber (SA), whereas the passive material is used to define the low-loss waveguides and current injection based phase shifters, as shown in Fig. 1. After regrowth, the waveguide is defined with photoresist on a Cr/SiO2 bilayer hard mask. The Cr is etched using a low power Cl2-based inductively coupled plasma (ICP), and the SiO2 is etched using an SF6/Ar based ICP. The resulting 600 nm SiO2 mask acts as a hard-mask to define the InGaAsP/InP deeply etched waveguides using a Cl2/H2/Ar(9/18/2 sccm) ICP at a chamber pressure of 1.5 mT. The resulting etched features are shown in Fig. 2. After removing the SiO2 mask, blanket deposition of a 350 nm isolation layer of silicon nitride is performed. Vias are opened for topside p-metal contacts. N-metal contacts are realized through backside deposition of Ti/Pt/Au onto the n-doped conducting InP substrate.The fully fabricated GFF MLL PIC has a round-trip cavitylength of 2600 μm, corresponding to lasing lines spaced by30 GHz, as shown in Fig. 3.

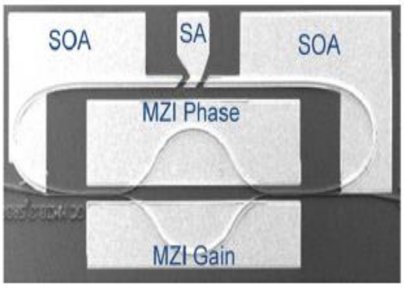
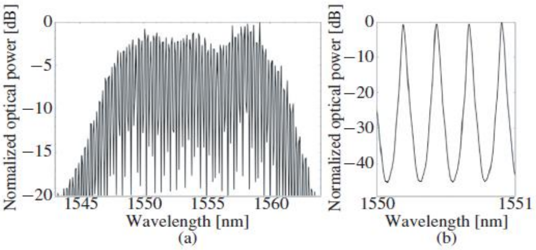


Fig. 3. SEM image of the GFF MLL PIC.



The 600 μm asymmetric MZI filter uses 3 dB, i.e., 50–50, multi-mode interference (MMI) couplers to form two arms, which differ in length by 16 μm providing a free-spectral-range (FSR) of 40 nm. One of the arms of the MZI filter has an SOA that can be used to control the extinction ratio (ER) of the GFF, whereas the other armhas a phase shifter allowing adjustment of the filter zero.

III. PHASE LOCKED COMB GENERATION

The GFF MLL PICs are mounted on copper carriers and Characterized at 10 °C using a thermo-electrical cooler (TEC). For passive mode-locking, the total drive current to the two 750 μm long ring SOAs (designated “SOA” in Fig. 3) is 110 mA with the 60 μm long SA biased at −4.5 V. The 460 μm long MZI gain section is driven at 31 mA with the 476 μm long MZI phase section set at 3 mA. The average power coupled into a lensed fiber is −6 dBm. The MZI filter gain and phase are adjusted to maximize the optical comb width as measured on an optical spectrum analyser (OSA), shown in Fig. 4(a). The −10 dB span of the comb is 15 nm (1.88 THz) with lines spaced by 30 GHz as determined by the cavity length. As shown in Fig. 4(a), the ripple between adjacent lasing lines is several dB, while comb span is much wider. For this reason, the −3 dB bandwidth often provides a poor comparison between different comb spectra, and the −5 dB and −10 dB bandwidths are more useful for characterization [4]. The optical signal-to-noise ratio (OSNR) over the standard0.1 nm bandwidth is >35 dB for all comb-lines, and 45 dB at the peak, as shown in Fig. 4(b). For the temporal pulse measurements on a second-harmonic generation (SHG) based autocorrelator, the output from the GFF MLL is amplified using a 30 dBm erbium doped fibre amplifier (EDFA); this optical amplification is necessary for measurements on the autocorrelator.

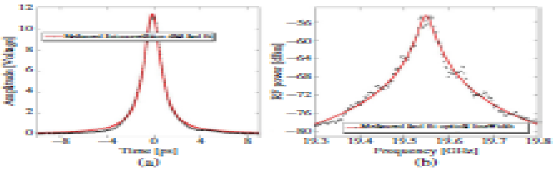


Fig. 5. (a) Measured and 900 fs Lorentzian fit pulse from an Inrad second harmonic generation based autocorrelator. (b) Heterodyne optical linewidth measurement of comb lasing line at 1555 nm. The Lorentzian linewidth fit has an FWHM of 29 MHz.

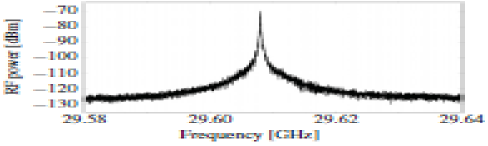


Fig. 6. Measured RF power from a 40 GHz photodiode with electrical signal analyzer (ESA). The −20 dB RF linewidth is 500 KHz (RBW = 50 KHz).

Fig. 5(a) shows the narrow pulses fit to a Lorentzian function with a full width half maximum (FWHM) of 900 fs and a corresponding time bandwidth product of 1.19, 5.4x larger than the time bandwidth limit of 0.22. Added sections of single mode and dispersion compensated fiber after the EDFA did not reduce the pulse width significantly, which suggests that the EDFA introduces higher-order dispersion into the broadband pulse. optical linewidth of the center of the comb is measured with a heterodyne method using a 40 GHz photodiode, ESA, and a narrow <100 KHz linewidth laser. Fig. 5(b) shows the Lorentzian fit optical linewidth with a FWHM of 29 MHz. The relative intensity noise (RIN) of a single mode is measured using a fiber Bragg filter centered at 1550 nm. The peak RIN is −82.6 dBc/Hz at 1.18 GHz for the 110 mA drive current. Fig. 6 shows the measured RF power from the mode-locked laser using a 40 GHz photodiode and an electrical spectrum analyser (ESA). A 30 dB low noise microwave amplifier boosts the electrical signal in the ESA (no EDFA is used).

The RF power is measured to be 50 dB above the noise floor at 50 KHz resolution bandwidth (RBW). The −20 dB linewidth is as narrow as 500 KHz, demonstrating sub-MHz frequency stability between adjacent lasing lines. For use in coherent communication systems, incorporating active mode locking into the cavity can further reduce this RF linewidth and provide precise frequency control over the mode spacing, thus enhancing the frequency stability between channels. As shown in Fig. 7, the single sideband phase noise is measured from 100 Hz to 30 MHz with a corresponding RMS jitter value of 4.6 ps. Nearly half of the RMS jitter is accrued at <100 KHz, which is likely due to vibrations on the optical bench and thermal instability.

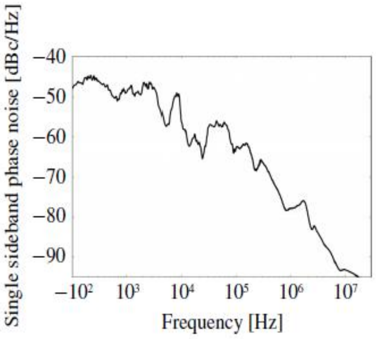


Fig. 7. Single sideband phase noise versus frequency. The integrated RMS jitter from 100 Hz to 30 MHz is 4.6 ps.

In practice, such low frequency noise that remains after packaging can be easily handled with receiver tracking and stabilization. We are unable to characterize the phase noise above 30 MHz, as the single sideband phase noise goes below the ESA noise floor.

IV. CONCLUSION

We have presented an integrated GFF MLL PIC and have Demonstrated the widest integrated MLL comb span from InPMQW based material. Changes to the cavity length can be made to accommodate frequency spacing from 10 to 40 GHz with near MHz accuracy, as determined by optical lithography. For sub-MHz frequency accuracy, active-mode locking techniques can be used. This 1.88 THz phase-locked comb source can have important applications in coherent communication systems, offset locking, and phase-locked sources for WDM.

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