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Comparison of Comb-line Generation from InGaAsP/InP Integrated Ring Mode-locked Lasers

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Abstract: We compare comb-line generation from a 30 GHz gain flattened ring mode-locked laser and two standard 30 GHz ring mode-locked lasers. The gain flattened ring has a 1.32 THz spectral width whereas the other devices have 420 and 630 GHz spectral widths.
OCIS codes: (250.5300) Photonic integrated circuits; (140.4050) Mode-locked lasers.

1. Introduction

InGaAsP/InP mode-locked lasers (MLLs) operating at 1.55µm wavelength are very stable pulse sources, which makes them attractive components for high-speed optical fiber communication [1]. Due to the multiple lasing modes that are necessary to form pulse-trains, these mode-locked lasers can also be used for frequency comb-line generation [2] and as multi-wavelength sources for coherent wavelength-division-multiplexing (WDM) [3]. Since the comb-line spacing is determined by the cavity length, integrated mode-locked lasers typically provide lines spaced at 10-100 GHz, which makes them suitable for the current and projected ITU grids. For this reason, a MLL that provides stable and broad comb-line generation has the potential to replace tens or hundreds of single channel DFB lasers. MLLs built on a highly versatile InGaAsP/InP material platform provide the capability to create photonic integrated circuits (PICs) with diverse functionality and systems-on-chip when combined with components that include: widely-tunable transmitters [4], tunable optical filters [5], and wavelength converters [6]. Furthermore, new applications in integrated offset frequency locking and light detection and ranging (LIDAR) will require stable and wide optical comb sources with lines spaced by 20-40 GHz. Such devices are based on the recently demonstrated integrated Optical Phase-Lock-Loop (OPLL) built on the InGaAsP/InP material platform [7]. The need for on-chip optical comb sources with GHz line spacing makes integrated mode-locked lasers a promising solution.

In a semiconductor mode-locked laser, the width of the generated comb spectrum is determined by the cavity dispersion and gain competition between the lasing modes. This gain completion occurs due to nonuniform material gain across wavelength. Intra-cavity gain flattening creates a more uniform gain profile by applying a filter with the inverse shape of the gain profile. Previously, sub-picosecond pulses with 4 nm spectral widths have been shown in a 30 GHz integrated MLL with a gain flattening filter [8].

By growing a broad distribution of different sized dots, quantum dot (QD) gain material can be grown to have a substantially broader gain bandwidth than quantum wells (QWs) or bulk. For this reason, integrated mode-locked lasers based on InGaAs QDs have shown a -3 dB spectral width of 14 nm at 1.3 µm [9], while MLLs based on silicon evanescent material platform using QWs have shown a -10 dB spectral width of 8 nm at 1.5 µm [2]. We present an InGaAsP/InP QW based ring mode-locked laser with a gain flattened filter (GFF) that provides -3dB and -10dB spectral widths of 10.5 nm and 15 nm respectively. We compare this result to two MLLs on the same material platform, without the GFF, which have -3dB spectral widths of 3.5 and 5 nm. The GFF incorporates an asymmetric Mach-Zehnder interferometer with one gain arm and one phase shift arm. This allows it to have a tunable extinction ratio and placement of the filter zero across the C-band. The GFF requires no additional processing steps and the entire device is defined by stepper lithography. The GFF can be used to improve the gain flatness on any material platform, including: QDs, QWs, and bulk. We have built the GFF on a standard QW material platform for ease of integration with other photonic devices previously demonstrated on this platform.

2. Experiments and Discussion

A standard offset quantum well (OQW) InGaAsP/InP integration platform was used with 7 QWs positioned above a 300nm thick 1.3Q waveguide (WG) with a confinement factor of 7.1%. A wet-etch removes the QWs for low loss passive WGs followed by a single blanket p-cladding regrowth. WGs were defined by stepper lithography on a photoresist/Cr/SiO_2 triple-layer mask. The patterned SiO_2 mask is used to mask the InGaAsP/InP in Cl_2/H_2/Ar etch chemistry with Inductively Coupled Plasma (ICP) Reactive Ion Etching (RIE).

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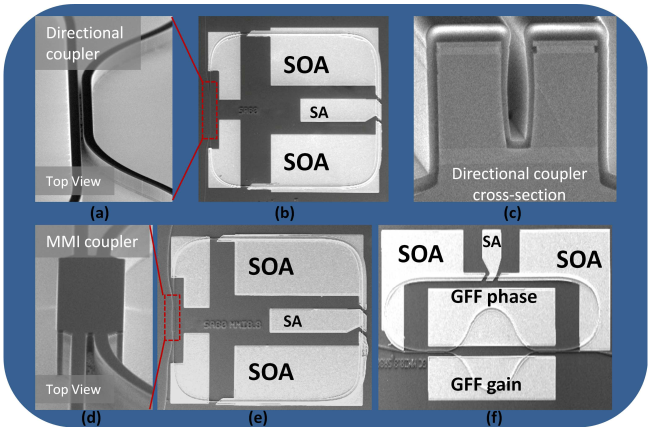

Fig. 1. Scanning electron microscope (SEM) images of (a) directional coupler (top view), (b) directional coupler based MLL, (c) directional coupler cross-section, (d) multimode interference (MMI) coupler, (e) MMI based MLL, and (f) MLL with gain flattening filter (GFF).

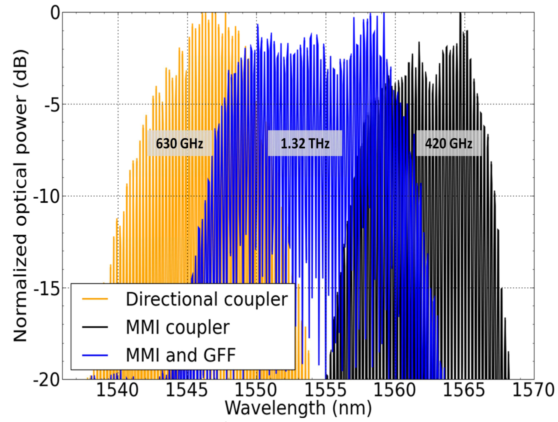

Fig. 2. Optical spectra from 30 GHz mode-locked lasers with a directional coupler, a multimode interference (MMI) coupler, and a gain flattening filter (GFF) with MMI couplers (-3dB freq. comb bandwidth is listed on each spectrum).

As seen in Fig. 1(a) and 1(b), the RIE lag effect, which acts to slow the etch rate of smaller features, was used to define a 125µm long directional coupler with ~2% power coupling on a deeply etched ring with a single etch-step [10]. As shown in Fig. 1(c), the directional coupler gap is 700 nm wide with an etch depth of ~2.5 µm, terminated right above the InGaAsP WG layer. As shown in Fig. 1(d) and 1(e), the ring waveguide and the 100µm long MMI with 50% power coupling, were created using a single 5 µm deep etch. These same MMI couplers were used to create the GFF, as shown in Fig. 1(f).

The drive current and absorber bias were varied to find the widest optical spectrum for each of the three devices. The laser outputs were measured with an optical spectrum analyzer (OSA), as shown in Fig. 2. To verify stable mode-locking, the devices were measured on an autocorrelator to observe pulse-trains and an electrical spectrum analyzer (ESA) to observe RF power. The -3dB spectral bandwidth of the MMI coupler based MLL, directional coupler based MLL, and GFF-MLL were 3.5 nm, 5 nm, and 10.5 nm respectively. These wavelength spans correspond to frequency comb widths of 420 GHz, 630 GHz, and 1.32 THz. The RF linewidth of the GFF-MLL was measured to be 600 KHz. This RF linewidth is typical for a passively mode-locked ring laser with QW gain material and can be reduced dramatically by active mode-locking using an RF drive signal. The optical linewidth was measured to be 30-60 MHz across the range of comb-lines using a heterodyne method with a high-speed photodiode, ESA, and a <1 MHz linewidth tunable laser. Narrower RF and optical linewidths improve the stability of integrated optical phase-locked loops and allow for higher QAM transmission in WDM.

In conclusion, we have fabricated integrated InGaAsP/InP comb generators based on 30 GHz ring mode-locked lasers. The mode-locked laser with a gain flattened filter generates a frequency comb that spans 1.32 THz.

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4. References

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