Optical and RF stability transfer in a monolithic coupled-cavity colliding pulse mode-locked quantum dot laser

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We report a novel quantum dot based laser design where a stable high-Q master laser is used to injection lock a passively mode-locked monolithic colliding pulse slave laser. Coupling between the crossed orthogonal laser cavities is achieved through a common monolithically integrated saturable absorber, which results in the locking and hence reduction of the timing jitter as well as the long-term frequency drift of the slave laser. A stable 30 GHz optical pulse train is generated with more than 10 dB reduction in the RF noise level at 20 MHz offset and close to 3 times reduction in the 10 dB average optical linewidth of the slave laser.

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Wide spaced frequency combs generated by short optical pulses at high repetition rates have become important tools for time and frequency metrology and as potential sources for coherent communications and signal processing [1,2]. Monolithic passively mode-locked lasers, especially quantum dot (QD) based lasers with unique characteristics, such as ultrabroad gain bandwidth, low threshold current, enhanced temperature stability, low linewidth enhancement factor, and ultrafast gain and absorption dynamics offer promise as compact, reliable, and robust optical sources [3,4]. However, in the absence of direct electrical modulation, these passively mode-locked lasers are susceptible to large amplitude and timing jitter instabilities [5]. Previous research has been focused on the external stabilization of pulse trains such as optoelectronic feedback using phase-locked loops [6], optical pulse injection [7], and subharmonic optical injection [8]. Recently, optical microresonators have also been demonstrated to serve as compact sources of optical frequency combs [9]. However, the complexity of all these techniques, and the fabrication and cost involved, limit their applications.

We report a novel and simple QD based laser design where a stable high-Q ring cavity is used to injection lock a passively mode-locked monolithic laser operating in colliding pulse regime. We believe four-wave mixing (FWM) in the common saturable absorber (SA) is responsible for the injection locking. However, the contributions of other mechanisms such as linear scattering, which are expected to be small, still need to be explored [10].

As seen in Fig. 1, the two curved gain sections are part of an external ring cavity, which is precisely built and passively mode-locked at a subharmonic of the monolithic colliding pulse laser. Having the two cavities in a crossed configuration would lead to the formation of transient gratings, when the four pulses overlap in the SA region. Synchronization of the four pulses occurs because minimum energy is lost to the SA when the four pulses meet in the absorber medium. The formation of the transient gratings (referred to as degenerate FWM) is due to the carrier density variation in the SA region, as observed in the case of a conventional colliding pulse mode-locked laser (CPM) [11,12]. The resulting index of refraction modulation at 45° to the face of SA causes the pulses to be diffracted from individual cavities into each other, which we believe couples and locks the CPM laser to the external cavity. This stabilizes and thus effectively reduces the jitter associated with the CPM laser, as witnessed by the considerable reduction in the RF and optical linewidth of the CPM laser.

The devices used in the experiment are fabricated from InAs/InGaAs QD wafer grown by molecular beam epitaxy on an $n+\langle 100\rangle$ GaAs substrate. The active region is a multistack QD structure, consisting of 10 layers of self-assembled InAs QDs capped by $In_XGa_{1-x}As$ quantum wells and bounded by AlGaAs cladding layers. Each QD layer is separated by 33 nm thick GaAs spacers. The emission wavelength is $\sim$1.3 μm.

The fabricated monolithic device structure is shown in Fig. 1. It consists of four gain sections with two crossed SAs at the symmetry center in order to maximize the coherent coupling of the four colliding pulses. Mesa

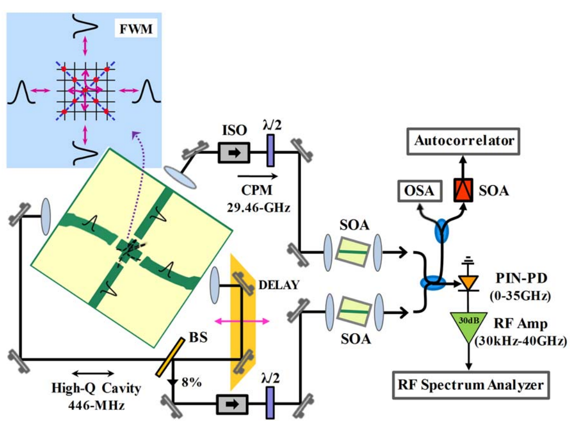

Fig. 1. (Color online) Schematic drawing of the experimental setup. FWM, four-wave mixing process; SOA, semiconductor optical amplifier; BS, pellicle beam splitter (92 – 8%); $\lambda/2$, half-wave plate; ISO, optical isolator; OSA, optical spectrum analyzer.

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structures are defined using standard ridge waveguide laser processing. The sample is wet-etched to form 3.6 and 4.6 μm wide single mode waveguides in the case of curved and linear sections, respectively. The curved section waveguides are designed at an angle of 7° with respect to the facet and are tapered to 4.6 μm widths at the termination to avoid Fabry–Perot (FP) reflections. The SA sections are 4.6 μm wide and 200 μm long waveguides, separated by a 15 μm gap from the gain sections. All the gain and SA sections facets are further angled relative to each other to avoid FP reflections. All four gain sections are electrically isolated from each other, allowing for individual control of the DC bias currents to help achieve optimal mode-locking. No antireflection (AR) coatings are used on the cleaved facets ($R \sim 32\%$). Single mode operation is verified with the effective index method and beam profiling and by efficient coupling to single mode fiber (SMF).

The monolithic CPM cavity formed by the cleaved facets has a total length of about 2.8 mm. However, because of the two counterpropagating pulses traveling simultaneously in the cavity, the fundamental repetition rate in the CPM configuration is twice the free spectral range (FSR) of the whole cavity. The CPM resonant cavity thus has a repetition rate of 29.46 GHz. For the master oscillator, the two curved sections serve as the gain medium. As seen in Fig. 1, the cavity is built with four gold coated external mirrors, with two mirrors mounted on a translation stage to control and precisely match the cavity length to a subharmonic of the CPM laser. The chosen cavity length corresponds to an FSR of 446 MHz, which is the 66th subharmonic of the CPM laser. In the operation mode, all the gain sections are driven by constant-current sources, while a voltage source provides the reverse bias to the absorber sections. It should be noted that because of the common SA region, the reverse bias voltage and the bias currents used in the experiment are carefully chosen to achieve simultaneous stable mode-locking of the external cavity and the CPM laser and to achieve optical spectral overlap of the two cavities. The spectral overlap induces coupling between the two cavities whereby the injected pulses transfer the phase stability to the longitudinal modes of the CPM slave laser, thus injection locking the CPM laser to the master laser.

To begin, the external ring cavity is first aligned to operate in a continuous wave (CW) regime by applying forward bias current of 70 mA on each of the two curved gain sections, using separate DC probes and current sources. The threshold current of the laser is ~35 mA (applied on each gain section with no voltage on the absorber section). Two aspheric lenses are used to collect and collimate the light inside the ring cavity. Passive mode-locking is achieved by applying reverse bias voltage of −6.5 V ± 0.1 V to the crossed SA section, which is kept constant through all measurements. The light is coupled out of the ring cavity using a pellicle beamsplitter with small reflectance (8%) to minimize the cavity losses. The output is amplified using a semiconductor optical amplifier (SOA) and then coupled to SMF fiber for diagnostics.

The spectral and autocorrelation measurements are shown in Fig. 2. The 3 dB spectral width is 3.6 nm. The pulsewidth is estimated to be 5.21 ps, assuming a Gaussian pulse shape. The time-bandwidth product (TBP) is thus 3.29, which is 7.5 times transform limit.

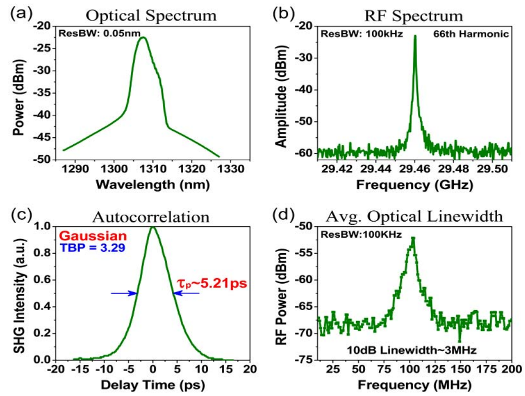

Fig. 2. (Color online) Spectra of the passively mode-locked high-Q external cavity (master) laser.

The optical linewidth in Fig. 2(d) is measured using the delayed self-heterodyne technique. The laser output is amplified using a fiberized amplifier before the Mach–Zehnder interferometer. A free space acousto-optic modulator operating at 100 MHz in one of the arms together with 200 m fiber delay in the other produces an uncorrelated beat tone at 100 MHz on the electrical spectrum analyzer, which gives us the measure of the average optical linewidth, as it is the result of a heterodyne beat of two combs. Since semiconductor laser linewidths are dominated by frequency jitter, or $1/f$ noise, linewidths are measured more accurately by determining the width at levels further down from the peak than the half-maximum. Due to the delayed self-heterodyne beat being a result of a convolution of Lorentzian curves, a deconvolution factor is necessary. For the 10 dB width, this factor is $2\sqrt{9}\Delta\nu$. The measured 10 dB average optical linewidth of the master laser is ~18 MHz, which thus yields a laser linewidth of $\Delta\nu = 3$ MHz, after deconvolution.

The slave CPM laser is passively mode-locked at the fundamental repetition rate of 29.46 GHz by applying a forward bias current of 28 mA on each of its linear gain sections. The reverse bias voltage is −6.5 V, which, as mentioned, is shared and kept constant with the SA of the master oscillator. The threshold current of the laser is ~20 mA (applied on each gain section with no voltage on the absorber section). Light is coupled out using an aspheric lens and then amplified using an SOA before going to the diagnostic equipment. As seen in Fig. 3(a), the laser exhibits supermode noise (a characteristic of harmonic mode-locking) with the optical spectrum showing two sets of optical modes spaced at the cavity FSR [2]. The measurements before injection are taken by physically blocking the light inside the master ring cavity. Optical pulse injection is achieved by removing this beam block. As seen in Fig. 3, supermode suppression in the optical domain is not only accompanied by RF linewidth reduction but also by reduction in the average optical linewidth after injection locking. There is a more than 10 dB reduction in the RF noise level at 20 MHz offset from the carrier. The RF tone width is reduced from 24.35 MHz to 4.88 MHz measured 30 dB down from the carrier, which is an almost 5-times reduction. This is accompanied by a reduction of the 10 dB average optical

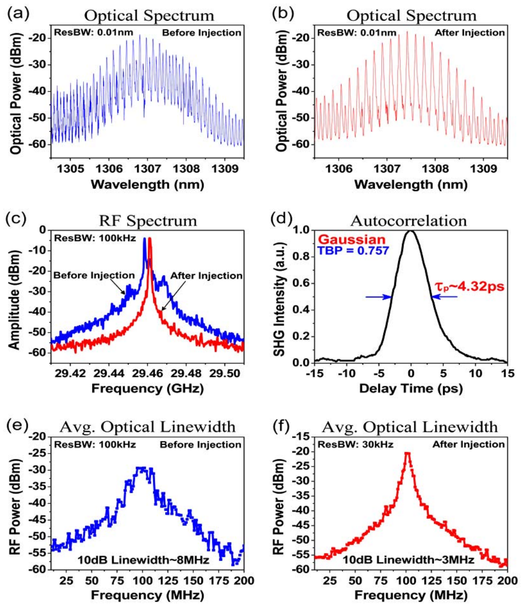

Fig. 3. (Color online) Spectra of the passively mode-locked CPM (slave) laser before (in blue) and after (in red) optical injection.

linewidth, from 46 MHz to 18 MHz. After deconvolution, this corresponds to a laser linewidth reduction from ∼8 MHz to 3 MHz after injection locking.

The intensity autocorrelation measurements are shown in Fig. 3(d). The pulsewidth is estimated to be 4.32 ps, assuming a Gaussian pulse shape. The 3 dB spectral width is 1 nm. The TBP is thus 0.757, which is 1.72 times the transform limit. The autocorrelation trace (and hence the pulsewidth) remains unaffected by injection locking.

The mechanism of stabilization can be explained as due to the optical pulse injection from the master laser into the CPM cavity, which injection locks the CPM laser to the stable master oscillator. Injection locking is confirmed by the supermode suppression and the reduction in the optical linewidth of the CPM laser, which is seen to closely match the linewidth of the master. The adjustment of the optical pulse timing of the CPM laser by the pulses of the master oscillator further leads to the sharpening in the RF spectrum peak and hence the RF linewidth reduction. However, the pulsewidth of the CPM laser remains the same after injection locking, indicating that the main pulse-formation mechanisms such as saturable absorption and saturable amplification are still dominated by the slave laser. Because the four pulse interaction is only occurring periodically (every 66th pulse of the slave laser), pulse shortening does not occur as might be expected with higher optical intensity in the SA. The injection locking may be due to a combination of FWM and linear scattering. Considering the small magnitude of linear scattering, which is shown to be −35 dB at waveguide angles of 31° [10], we expect the contribution due to scattering to decrease at larger angles such as 90° used in our design. Also the linear coupling between the orthogonal waveguides is further reduced since the polarization of the light is TE and coupling into an orthogonal waveguide would have the k-vector and polarization of the scattered light being in the same direction, making the light a longitudinal wave, which is not allowed. We thus hypothesize that FWM plays a dominant role in our case; however, further experiments are required to confirm this effect.

In summary, we have demonstrated a novel, simple, compact, and cost-effective QD based laser design at 1.3 μm using standard fabrication processes. A stable high-Q passively mode-locked master laser is used to injection lock a passively mode-locked CPM slave laser. FWM in the common SA region is believed to be the contributing mechanism for the interaction and locking of the slave laser. This leads to almost 5-times reduction in the width of RF tone (from 24.35 MHz to 4.88 MHz) measured 30 dB down from the carrier. The RF noise level is reduced by more than 10 dB at 20 MHz offset after locking, and close to 3-times reduction of the 10 dB average optical linewidth (from 8 MHz to 3 MHz) is observed. These improvements confirm the potential of the new laser design as a compact, reliable, and robust source of high repetition rate optical pulses and for use in an all passive stabilization architecture.

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References

1. Th. Udem, R. Holzwarth, and T. W. Hänsch, Nature **416**, 233 (2002).
2. P. J. Delfyett, I. Ozdur, N. Hoghooghi, M. Akbulut, J. Davila-Rodriguez, and S. Bhooplapur, IEEE J. Sel. Top. Quantum Electron. **18**, 258 (2012).
3. M. G. Thompson, A. R. Rae, M. Xia, R. V. Penty, and I. H. White, IEEE J. Sel. Top. Quantum Electron. **15**, 661 (2009).
4. E. U. Rafailov, M. A. Cataluna, and W. Sibbett, Nature Photon. **1**, 395 (2007).
5. D. J. Derickson, P. A. Morton, J. E. Bowers, and R. L. Thornton, Appl. Phys. Lett. **59**, 3372 (1991).
6. X. S. Yao, L. Davis, and L. Maleki, J. Lightwave Technol. **18**, 73 (2000).
7. B. K. Mathason and P. J. Delfyett, J. Lightwave Technol. **18**, 1111 (2000).
8. S. Arahira and Y. Ogawa, IEEE Photon. Technol. Lett. **14**, 537 (2002).
9. P. Del'Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, Nature **450**, 1214 (2007).
10. C. van Dam, F. P. G. M. van Ham, F. H. Groen, J. J. G. M. van der Tol, I. Moerman, and M. K. Smit, in *Proceedings of Conference on Integrated Photonics Research* (Optical Society of America, 1996), paper IMH1-1.
11. D. Kühlke, W. Rudolph, and B. Wilhelmi, Appl. Phys. Lett. **42**, 325 (1983).
12. J. Buchert, R. Dorsinville, P. Delfyett, S. Krimchansky, and R. R. Alfano, Opt. Commun. **52**, 433 (1985).