Demonstrating Bidirectional Coupling Using a Monolithically Integrated Tunable Comb Source

(Student paper)

John McCarthy[1,2], Diarmuid O'Sullivan[2], Maryam Shayesteh[3], Mohamad Dernaika[1] , Bryan Kelleher[1,2] and Frank Peters[1,2]

[1]Tyndall National Institute, Lee Maltings, Cork City, Ireland
[2]Physics Department, University College Cork, College Road, Cork City, Ireland
[3]University of Southampton, Southampton, Hampshire, UK
[*] john.mccarthy@tyndall.ie

A bidirectionally coupled comb is demonstrated using a monolithically integrated Photonic Integrated Circuit (PIC). The tunable comb source is created by gain switching a slave Fabry-Pérot laser that is injection locked to a master slotted Fabry-Pérot laser. The master section of the PIC produces a single mode spectrum with a tunable range of 1557nm – 1573nm. Bidirectional coupling is observed as the comb is detected through the facet of the gain switched slave laser as well as through the facet of the single mode master laser.

Keywords: *Frequency comb generation, gain switching, bidirectional coupling*

INTRODUCTION

Optical frequency comb sources (OFCS) show significant promise in many modern day applications such as spectroscopy [1], space based instruments [2] and high speed telecommunications [3]. OFCS generate equally spaced spectral carriers with a known phase and relation between adjacent carriers. Due to their precise and stable frequency and relative phases, they can be used in wavelength division multiplexing (WDM) communications to create coherent optical superchannels, where guard bands between neighbouring WDM signals are no longer required [4]. One method of generating optical frequency combs in a PIC (which is the method described in this paper) is by injection locking a slave laser with a single mode master laser and gain switching the slave laser by applying a high power radio frequency (RF) signal.

The comb source itself is demonstrated by injection locking a gain switched slave laser to a single mode master laser. Injection locking using an external master laser has previously been demonstrated to reduce phase noise and linewidth in gain switched lasers [5]. In this work, these two lasers are integrated in a strongly coupled master slave configuration [6], whereby the slave laser is optically phase locked to that of the master. The single mode characteristics of the slave laser has been known to improve by on-chip optical phase locking, particularly with increasing the side mode suppression ratio (SMSR) of the slave [7]. The master laser is more heavily biased than the slave, and so the two sections are operating in an asymmetric bias regime. So while no isolator exists between the two lasers, the asymmetry of the operation has been known to allow for injection locking [8]. The slave laser is then gain switched by a high power RF signal to generate the optical combs.

In this paper, we focus on an on-chip phenomena whereby the generated comb is measured through both the end facet of the master and end facet of the slave laser where it is generated. This is a demonstration of bidirectional coupling due to the relative short lifetime of the generated photons. This is an advantage for future PIC designs as it allows for a comb to be propagated along different outputs without requiring a more complicated design.

DEVICE DESIGN

The device was fabricated with commercially available material designed for the emission at 1550 nm, purchased from IQE. The lasing material consists of 5 compressively strained 6 nm wide AlGaInAs quantum wells on an n-doped InP substrate. The upper p-doped cladding consists of a 0.2 µm InGaAs cap layer, which is followed by a 0.05 µm of InGaAsP, lattice matched to 1.62 µm of InP. The ridge and slot features are defined by standard lithographic techniques, with a ridge width of 2.5 µm and a height of 1.7 µm, and a slot width of 1 µm, with the ridge etch stopping above the quantum wells [9]. The slots were used for both optical reflection, as well as electrical isolation between the different sections of the PIC. A ground-signal-ground (GSG) contact was added to the slave section to allow for the high-frequency gain switching of the device.

The master section of the device is made up of a gain section, 600 µm in length, and a mirror section. The mirror section is made up of 8 slots with an interslot separation of 108 µm. These slots act as reflective defects along the ridge by creating regions of lower effective refractive index, effectively creating a master laser that is both single mode and tunable [5,10]. This master laser couples through a deep etched isolation slot and is integrated with a 1100 µm deep etched waveguide. This waveguide is in turn integrated with a 410 µm slave laser via another deep etched facet.

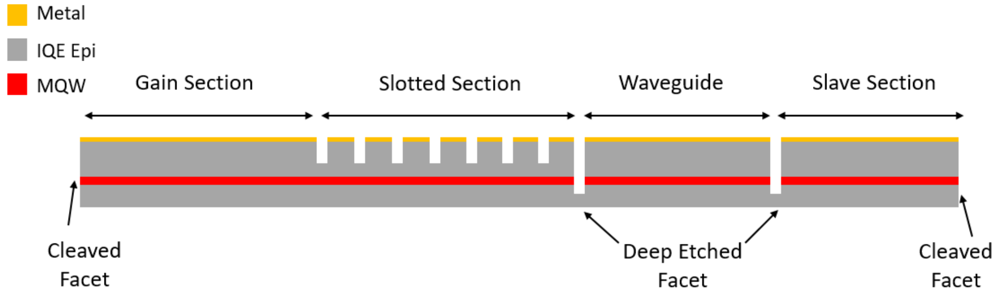

Fig. 1. Side view of PIC design.

RESULTS

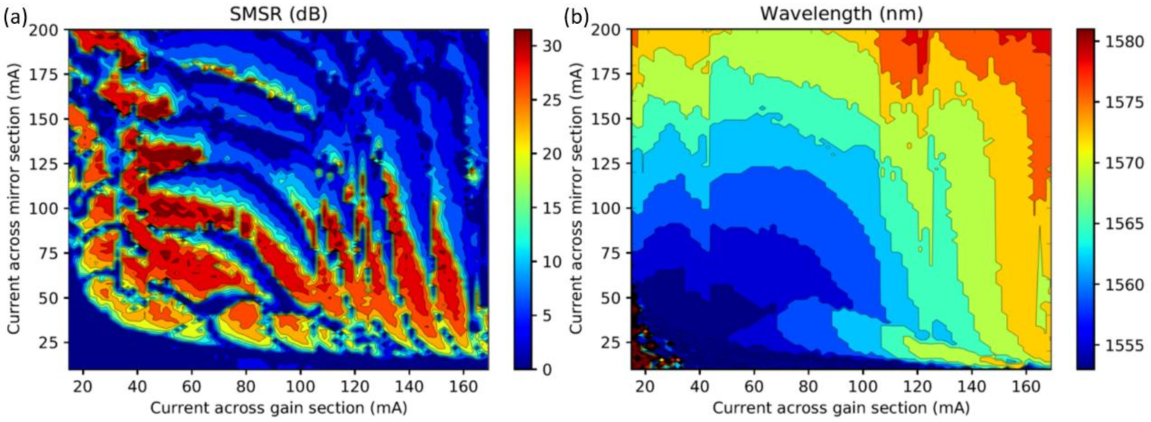

Fig. 2. (a) SMSR and (b) lasing wavelength of the master laser.

The master laser was initially characterized by biasing the gain and mirror sections of the device independently, sweeping the current through both sections and measuring the spectra through the cleaved facet of the master laser at each interval. The SMSR and lasing wavelength were recorded and plotted as shown in Fig. 2.

When the single mode nature of the master laser was determined, the deep etched waveguide was biased enough to make the waveguide passive, The slave laser was also biased just above threshold current and the spectra of the slave laser was optically phased locked to that of the master. A strong RF signal was applied to the slave laser to allow for gain switching to occur and a comb to be generated.

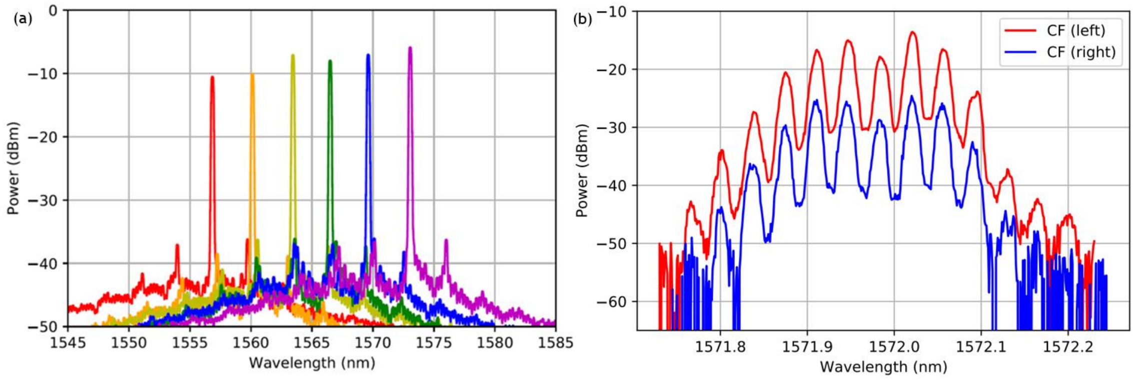

Fig. 3. (a) Single mode spectra determined by the master laser (b) Generated combs measured through the left and right facets.

Once the generated comb was detected through the slave laser facet (the right facet in Fig. 1), the comb was also detected through the master laser facet (the left facet). This is demonstrated in Fig.3(b).

This phenomenon is an example of bidirectional coupling which occurs between the single mode and gain switched lasers, and using the delayed differential equation model, simulations support these results (Fig. 4). The delay in the injection from the physical space between the lasers is also taken into account. The delay is normalized to the photon lifetime and this value is adjusted to determine the effect of the delay, and by doing so, the effect of the size of the device. As demonstrated in Fig. 4, the bidirectional model works best at producing combs at small delays. This is consistent with the experimental results as it is an on-chip device.

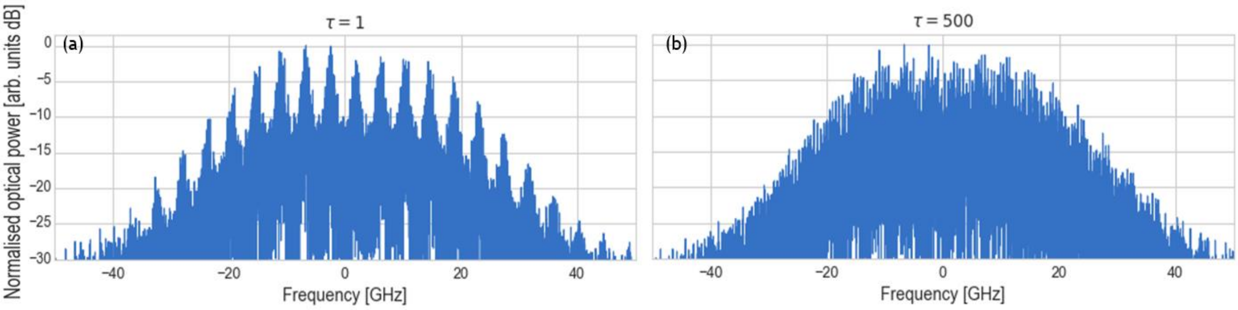

Fig. 4. Simulation of a bidirectional comb with a photonic lifetime of (a) 10 ps and (b) 5 ns.

CONCLUSION

This PIC demonstrates how a bidirectional coupled comb can be attained with an on-chip device. An optical frequency comb was obtained from the PIC by gain switching a slave laser that has been injection locked to a single mode master laser. Due to the reflective defects caused by the slots used in the mirror of the master, the master laser was shown to have a single mode and tunable wavelength. The short photon lifetime of the on-chip device allows for the bidirectional coupling to occur, as the comb generated by the gain switched slave laser is also detectable through the master laser. This is an advantage for future PIC designs as it allows for a comb to be propagated along different outputs without requiring a more complicated design.

ACKNOWLEDGMENTS

This work was supported by Science Foundation Ireland under grants 12/RC/2276 (IPIC), and SFI/13/IA/1960.

References

[1] I. Coddington, W. Swann, and N. Newbury, “Coherent multiheterodyne spectroscopy using stabilized optical frequency combs,”

[2] X. Wang, S. Takahashi, K. Takamasu, and H. Matsumoto, “Space position measurement using long-path heterodyne interferometer with optical frequency comb,” Opt. Express 20(3), 2725-2732 (2012).D. Jones, *Title of publication*, Journal name, vol. 1, no. 2, pp. 121-127, 2012

[3] A. Ellis and F. Gunning, “Spectral density enhancement using coherent WDM,” IEEE Photon. Technol. Lett. 17(2), 504-506 (2005).

[4] R. Zhou, P. M. Anandarajah, D. G. Pascual, J. O’Carroll, R. Phelan, B. Kelly, and L. P. Barry, “Monolithically integrated 2-section lasers for injection locked gain switched comb generation,” Optical Fiber Communications Conference and Exhibition (2014).

[5] L .Barry, P. Anandarajah, and A. Kaszubowska, “Optical pulse generation at frequencies up to “0 GHz using external-injection seeding of a gain switched commercial fabry-perot laser,” IEEE Photonics Technol. Lett. 13, 1014-1016 (2001).

[6] J. K. Alexander, P. E. Morrissey, H. Yang, P.J. Marraccini, B. Corbett, and F. H. Peters, “Monolithically integrated low linewidth comb source using gain switched slotted fabry-perot lasers,” Opt. Express 24, 7960-7965 (2016).

[7] A. Tauke-Pedretti, G. A. Vawter, E. J. Skogen, G. Peake, M. Overberg, C. Alford, W. W. Chow, Z. S. Yang, D. Torres, and F.Cajas, “Mutual injection locking of monolithically integrated coupled-cavity DBR lasers,” IEEE Photonics Technol. Lett. 23, 908-910 (2011).

[8] A. H. Perrott, L. Caro, M. Dernaika, and F.H. Peters, “A comparison between off and on-chip injection locking in a photonic integrated circuit,” Photonics 6 (2019).

[9] Zhengkai Jia, Hua Yang, Alison H. Perrott, Hui Wang, and Frank H. Peters, "Study on the proximity of QWI in InP-based AlGaInAs MQWs using the IFVD method and its application in single frequency teardrop laser diodes," Opt. Express 28, 31904-31913 (2020)

[10] Q. Y. Lu, W. H. Guo, R. Phelan, D. Byrne, J. F. Donegan, P. Lambkin, and B. Corbett, “Analysis of slot characteristics in slotted singlemode semiconductor lasers using the 2-D scattering matrix method,” IEEE Photonics Technol. Lett. 18, 2605-2607 (2006).