An integrated laser with on-chip optical feedback for random bit generation

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We discuss the design and testing of a laser integrated with a long on-chip optical feedback section. The device and feedback section have been fabricated on a generic photonic integration platform using only standard building blocks. A 10 cm feedback length is integrated on a footprint of 5.5 mm^2. We are able to control the amount of feedback by adjusting the injection current on SOAs which have been placed in the feedback loop. In doing so, we achieve chaotic dynamics in the long-cavity regime and show that the resulting dynamics can generate random bits based on the chaotic intensity fluctuation at a rate of 500 Mbits/s.

Introduction

The dynamics induced in semiconductor lasers by a long optical feedback loop has been studied in several papers [1], showing that feedback can lead to a large range of phenomena such as low-frequency fluctuations and chaotic intensity dynamics. Notwithstanding these studies, there is still considerable research interest in this system as a laser with feedback is on the one hand an ideal test-bed to experimentally study delay induced dynamics, and on the other hand useful for a range of novel applications. For example, semiconductor lasers with feedback have been used to demonstrate chaos synchronization in an optical telecommunication system, to realize high-speed random number generation and are used in new computational approaches such as reservoir computing [2]. In recent years, effort has been put into trying to implement the delay on-chip as this approach offers some important advantages: it will make the system more compact, robust, low-cost and avoids the complex and sensitive mechanical alignment between laser and feedback waveguide.

Results

The difficulty with the existing on-chip delay systems is that they typically make use of some very specific components that are intimately linked with the proprietary fabrication facilities. As such, it is difficult for other research groups to use this technology in their system design. Also, the work presented in literature is so far limited to relatively small delay lengths of about 1 cm. We have designed and experimentally characterized a semiconductor laser with on-chip integrated optical feedback using the standard building blocks of the generic Jeppix platform for photonic integrated lasers. The design is based on a DBR laser with a spiral delay waveguide (See Fig. 1.). We have included several control pads with which we can tune the fabricated laser's emission wavelength, the feedback strength and phase in order to compensate for fabrication tolerances. We implement a delay length of approximately 10cm.

Figure 1. Schematics of the integrated photonic chip used in the experiments. A Distributed Bragg Reflector (DBR) laser connected to two consecutive spirals, comprising the delay line. The semiconductor optical amplifiers (SOA) compensate for the losses in the delay line and the DBR on the far right completes the feedback loop.

We have recorded time traces of the emitted intensity for various values of the feedback strength, which is increased by increasing the pump currents of SOA1 and SOA2 in Fig. 1. At the right-hand side chip facet, we can monitor the spectral position of both the laser emission and the reflection band of the feedback DBR. The DBR has a reflection band that has a full width at half maximum of 2 nm, and we make sure that the laser line is spectrally aligned with this reflection band. Unfortunately, we do not observe any signatures of delay-induced dynamics even when the maximum current of 40mA is injected in both SOA1 and SOA2. We attribute this to the fact that the maximum feedback in the system is lower than expected. We can compensate for this small amount of feedback by lowering the reflection coefficient of the laser's front DBR mirror, because this will result in a larger percent- age of the light being coupled back in the laser cavity. Therefore, we spectrally detune the laser's front DBR with respect to the laser's rear DBR by pumping (only) the front DBR. This results in a shift of the reflection spectrum of the front DBR and of the laser's emission wavelength, whereby the reflection spectrum shifts more strongly. As a result, we see that the threshold current of the laser gradually increases when increasing the front DBR current. At the same time, the slope of the PI curve will increase such that the output power at a fixed ratio between pump current and threshold current (e.g. at twice the threshold current) initially increases. Eventually, when the front and rear DBR are completely spectrally detuned with respect to each other, the threshold current increases strongly. We have experimentally identified that a front DBR current of 1.9 mA results in a good compromise between high output power and reasonable increase in threshold current. The threshold current is increased to 22.5mA, and the output power at twice the threshold has also substantially increased to 160 µW. The emission wavelength at a pump current of 30 mA is 1551.4 nm. More importantly, the time traces of the laser output intensity now clearly show feedback induced dynamics when the SOAs in the feedback loop are biased. This is illustrated in Fig. 2, where we plot the photodetector signal (measured with a bandwidth of 2.4 GHz) at a bias current of 30 mA when the SOAs are un- pumped (top) and when the SOAs in the feedback loop are pumped (bottom). Without pumping the SOAs (i.e. for a small feedback strength) only small intensity fluctuations are observed in the time traces, but the amplitude of the intensity fluctuations rapidly grows if the feedback strength is increased.

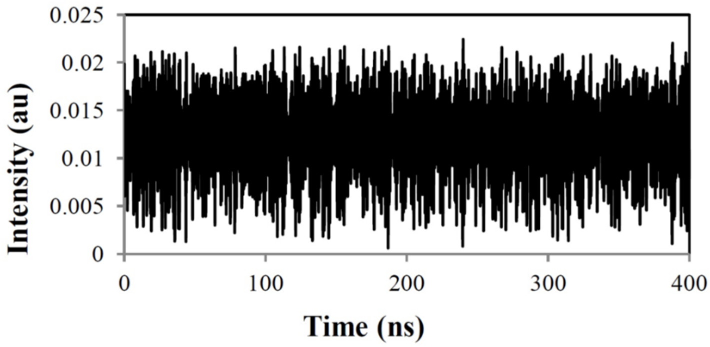

Figure 2. Time traces of the laser intensity at a laser pump current of 30mA when the front DBR current is 1.9mA

We have shown - using the NIST statistical test suite for random number generators - that the observed delay dynamics is sufficiently complex for random number generation [3]. We have set the sample time of the oscilloscope to 10ns, and we record time traces containing 8 million sample points for statistical analysis. The parameter values (i.e., current injected in the laser, the laser front mirror, SOA1 and SOA2) are selected to correspond to the maximum of the dynamic range of the chaotic signal. In order to fully exploit the dynamical fluctuations in the intensity to maximize the random bit generation rate, we will use a multi-bit analog to digital convertor (ADC) to digitize the photodetector signal. We use an 8 bit ADC for this purpose. Then, to enhance the uniformity of the generated sequence and also to eliminate any remaining correlations induced by the intrinsic dynamics and delay times, the 3 most significant bits (MSBs) are discarded. The results of the NIST test are shown in Table I. The tests are performed using 100 sequences of 400 kbit each. As can be seen, all the tests pass, verifying that our system produces a statistically random bit-stream. Since the sampling rate is 100 MSamples/s, this system is therefore capable of producing random bits at a rate of 500 Mb/s. We want to remark that we also tried to discard a lower amount of MSBs (i.e., less than 3), but in that case not all tests in the NIST test suite are passed successfully. Discarding a larger amount of MSB (e.g., 4 or 5 MSBs) also leads to a random bit stream that passes the NIST test suite, but in that case at a lower bit generation rate.

Table 1 NIST SP 800-22 statistical test results using 100 sequences of length 400 kbit. The significance level is set to 0.01, corresponding to a minimum P-value (i.e., the uniformity of p values) of 0.0001, and a minimum proportion of 0.96. For tests that produce multiple values, the worst case is shown.

Test	P-value test	Proportion	Pass/fail
Frequency	0.534	0.99	Pass
Block frequency	0.213	0.99	Pass
Cumulative sums	0.88	0.97	Pass
Runs	0.534	1.00	Pass
Longest run	0.109	0.98	Pass
Rank	0.384	1.00	Pass
FFT	0.817	1.00	Pass
Nonoverlapping template	0.0067	0.96	Pass
Overlapping template	0.740	0.98	Pass
Universal	0.779	1.00	Pass
Approximate entropy	0.130	0.98	Pass
Random excursions	0.045	0.98	Pass
Random exc. variant	0.0033	0.98	Pass
Serial	0.514	0.97	Pass
Linear complexity	0.456	1.00	Pass

Conclusions

In this paper we have shown that it is possible to use a generic photonic integration platform in order to fabricate a laser with integrated optical delay that is sufficiently long and strong to reach a chaotic dynamical regime that can be used to generate random bits. As the effective feedback strength turned out to be lower than initially estimated, we had to increase to outcoupling from the front mirror in order to reach the chaotic regime. Therefore, it is better in future designs to start with a lower reflection coefficient of this laser mirror and an increased reflection of the DBR in the feedback loop. Because of fabrication tolerances, it turned out to be essential to be able to shift the wavelength of either the laser or the feedback mirror, such that both can spectrally be aligned.

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