Phase noise characterization of injection locked semiconductor lasers to a 250 MHz optical frequency comb

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Abstract: Two lasers are simultaneously injection locked to the same comb mode and the injection locking quality is assessed in terms of phase noise and phase variance (1 kHz-10 MHz) for various injected powers.

OCIS codes: (120.5050) Phase measurement; (140.3520) Lasers, injection-locked

1. Introduction

Optical frequency combs (OFCs) commonly have applications in metrology due to the high frequency stability of the comb modes which can be achieved [1]. These highly stabilized combs also have potential applications in other fields such as arbitrary waveform generation, sensing, terahertz generation and telecommunications. However, these applications have yet to be fully exploited due to the small amount of power in each individual comb mode and also the difficulty in isolating and manipulating the separate comb modes individually. Optical injection locking has been identified as a method to overcome these potential issues by using multiple lasers which are injection locked to individual comb modes.

We have previously demonstrated highly stable long-term injection locking of a semiconductor laser to a single mode of a 250 MHz optical frequency comb, even when hundreds of comb modes were present in the injected signal [2]. We characterized the long-term locking stability by measuring the frequency variations every one second over eight hours and calculating the Allan deviation, which is particularly useful in the field of metrology. However, we had not carried out any analysis on the short-term phase fluctuations which are of prime importance in many other applications (e.g. terahertz generation, telecommunications, etc.). It is worth noting that in many of these applications at least two lasers need to be locked to the OFC.

In this investigation, we characterize the locking performance in terms of phase noise and phase variance of two semiconductor lasers optically injection locked to an OFC. To separate the noise of the comb itself from that due to the injection locking, both lasers in our characterization were locked to the same comb mode.

2. Experimental set-up

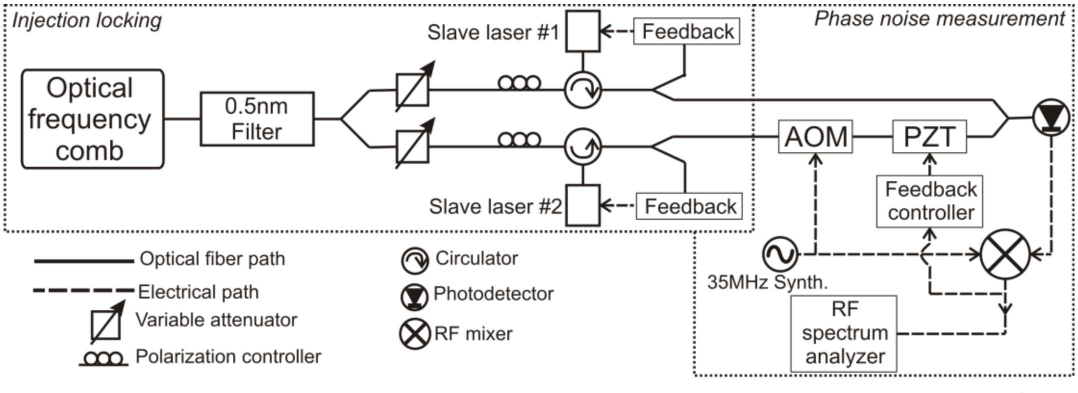

Fig. 1. Experimental set-up. AOM: acousto-optic modulator (35MHz), PZT: Piezoelectric transducer (phase shifter)

The experimental set-up is shown in Fig. 1. The carrier-offset-stabilized optical frequency comb (Menlo Systems FC1500-250-WG) had a repetition rate of 250 MHz. The slave lasers were both discrete mode semiconductor lasers without isolators (Eblana Photonics, Dublin). Narrow band pre-filtering of the comb was avoided by using low injection ratios (<-50dB per comb mode). This resulted in a narrow locking range containing just a single comb mode which the slave laser can lock to [2]. Long-term locking was achieved by using an electronic feedback scheme acting on the drive current to compensate for slow frequency variations [2, 3].

To offset the beating between the two lasers, one of them was frequency shifted by 35 MHz using an acousto-optic modulator. The phase noise of the beat signal was measured using an analogue RF frequency mixer. The fiberized piezoelectric phase shifter kept the mixer input signals in quadrature to ensure the mixer behaves as a phase detector.

3. Results – Phase noise and variance

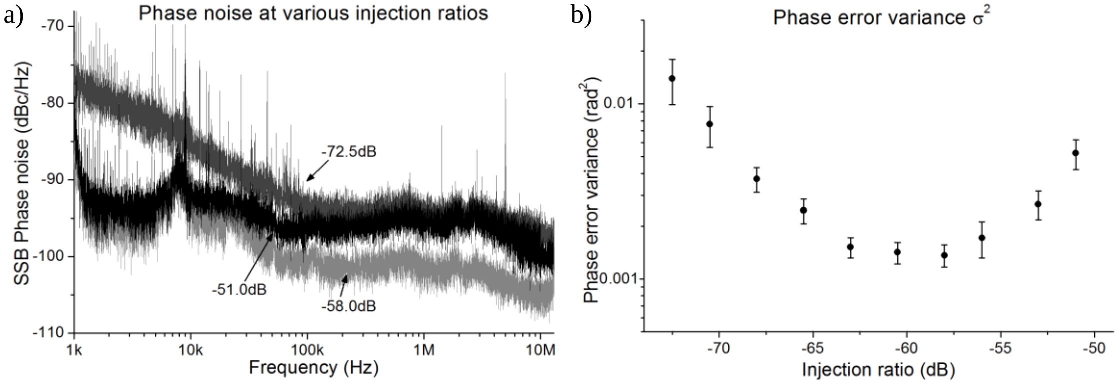

Fig 2. a) Single sideband (SSB) phase noise of an injection-locked laser in respect to the comb from 1 kHz to 13 MHz using injection ratios of -72.5, -58 and -51 dB (the two lasers are considered to be identical). b) The phase error variance of a single laser calculated by integrating the phase noise over the entire measured bandwidth.

The single sideband (SSB) phase noise of a single laser was measured for injection ratios (power per comb mode divided by the slave output power, which was approximately 13 dBm) ranging from -72.5 to -50 dB. Examples of the phase noise spectra are shown in Fig. 2a. The phase noise measurements were typically 50 dB above the noise floor. The contribution of amplitude noise to the measurement was found to be -30 dB of the measured phase noise.

The peak near 10 kHz, which is present at larger injection ratios, is due to the transfer of phase noise from the master comb to the injection locked slave laser. This could be suppressed by carefully matching the optical path lengths between the two slave lasers. The phase noise at an offset frequency of 1 MHz for an injection ratio of -58 dB is comparable to that in [3], despite using a lower injection ratio (~10 dB lower) and smaller comb spacing (250 MHz rather than 12 GHz).

The phase error variance was calculated by integrating the spectral density of the phase noise from 1 kHz to 13 MHz and is shown in Fig. 2b. An optimal injection ratio exists between -63 and -58 dB where the variance is at a minimum of less than 0.002 rad^2. Considering a Gaussian noise distribution, this corresponds to standard deviation which is less than 3 deg. At injection ratios lower than this optimum region, the overall phase noise increases (Fig. 2a) as the reduced locking range makes it harder to maintain injection locking. When the injection ratio is increased beyond the optimum range, the locking range becomes too large such that the neighboring comb modes begin to influence the locked laser through effects such as frequency pulling. This causes the phase noise and variance to increase.

4. Conclusion

The phase noise of an injection locked semiconductor laser to an optical frequency comb has been measured at low injection ratios (-58 to -72 dB), allowing direct locking to a low-repetition rate comb (250 MHz). This was done by simultaneously locking two similar lasers to the same frequency comb mode. It was found that the phase noise and corresponding phase error variance was at a minimum when the size of the locking range balanced the effects of interfering neighboring modes and reduced locking quality. The locking within the optimum injection ratio region had a standard phase deviation of less than 3 deg, which is suitable for most applications. This finding will help us to optimize our injection ratios when locking together more lasers.

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5. References

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