Utility of the Period-One Oscillation State in Injection-Locked Semiconductor Lasers

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Abstract: The period-one state of injection-locked semiconductor lasers represents a convenient way to generate microwave tones using only steady state biasing conditions. Recent developments will be reviewed along with comments on the practicality of these sources.

Index Terms — RF Oscillators, Tunable Oscillators, Injection Locking

Introduction
Injection-locked semiconductor lasers have been investigated for a number of applications over many years. Interest has primarily focused on the stably locked regime of injection locking [1] and dynamical regimes which produce waveforms exhibiting chaos [2]. Since the mid 2000’s the so-called period-one regime/state of injection locking has received increased attention for its ability to generate microwave tones while only requiring steady state biasing and temperature control of the master and slave lasers [3][4][5].

Ongoing work in this area continues to be motivated by the generation of microwave signals which is a relevant topic for myriad applications and will likely remain so for the foreseeable future. In our case, optical approaches to microwave generation provide opportunities to leverage the “speed” provided by photonics to address applications where electronics is currently a limiting factor. What remains unclear today is whether the performance of injection-locked systems operating in the period-one regime can be improved to the point where they can rival that of other available electronic sources and/or other optical approaches [6][7].

Experiment
In this work experimental results obtained using DFB lasers will be presented. Specifically, dense measurements made across much of the injection-locking parameter space for a DFB laser will be presented and discussed. Such an experimental “map” allows for the microwave components to be extracted as a function of both injected master-laser power and master-to-slave detuning, as partially depicted in Fig. 1(left). Clearly it is not just the the microwave frequency that is important but also the microwave linewidth, strength, and suppression ratio which all need to be more rigorously understood in order to further work in this area, particularly if one is to develop a viable system. As a consequence, the findings seen in Fig. 1 will be explored in greater detail and accompanied with results and comments regarding the behavior of the microwave output including its strength, linewidth, etc.

Modeling
Having the ability to perform numerical simulations, able to predict the experimentally observed behavior, is highly desirable since such models can be used to provide insight into the dynamics of this coupled nonlinear system. Indeed, such simplified models allow us to isolate the fundamental behavior of the underlying system and can therefore be used to illuminate opportunities to improve the experimental performance of the system e.g. reducing its environmental sensitivity and/or linewidth. In this case our model is based on a well-known system of coupled differential equations with a slight modification for the gain term as written in Eqs. (1)–(4) [7]:

\[
\frac{dA}{dt} = \left[-\frac{\gamma_c}{2} + i(\omega_0 - \omega_i)\right]A + \frac{\Gamma}{2}g(N, |A|)A + \eta A e^{-i(\omega_0 - \omega_i)t} \\
\frac{dN}{dt} = \frac{J}{ed} - \gamma_N N - \frac{2e_0 n^2}{\hbar \omega_0} g(N, |A|)|A|^2 \\
g(N, |A|) \overset{\text{def}}{=} \text{Re}[g(N, |A|)] \\
g(N, |A|) = g_0(N_0, A_0) + (1 - i\beta) \frac{\partial g}{\partial N} \bigg|_{N_0, A_0} (N - N_0) + (1 - i\beta') \frac{\partial g}{\partial |A|^2} \bigg|_{N_0, A_0} (|A|^2 - A_0^2)
\]

Although Eqs. (1)–(4) are relatively simplistic they are nevertheless capable of capturing the experimental behavior remarkably well [2]. This claim is reinforced by comparing Fig. 1 (left) with Fig. 1 (right) and noting that many of
the parameters used in the model relied on values typical in DFB lasers; no effort was made to “fit” the model to the experiment here. For example, the large shift in the x axis appears because only a fraction of the “Master Laser Power” gets injected into the slave laser as captured by the “Injected Strength”.

Fig. 1. (left) Experimentally measured period-one frequency (in GHz). (right) Numerically simulated period-one frequency (in GHz).

Conclusion
Work in injection locking has continued for many years and recently proved valuable in a number of relevant applications (including the one discussed in Ref. [1]). While the regime of injection locking investigated in this abstract is markedly different than that explored in many other efforts, it too may provide distinct benefits of its own. Nevertheless, the utility of the period-one regime is still an issue being heavily researched and this work will seek to discuss some of these open questions with respect to new findings.

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