AFRL-RY-WP-TP-2013-0023

TUNABLE PHOTONIC MIRCROWAVE OSCILLATOR SELF-LOCKED BY POLARIZATION-ROTATED OPTICAL FEEDBACK (PREPRINT)

Nicholas G. Usechak and Vassilios Kovanis

Optoelectronic Technology Branch
Aerospace Components & Subsystems Division

T.B. Simpson

L-3 Applied Technologies, Inc.

Jia-Ming Liu and Mohammad AlMulla

University of California, Los Angeles

JANUARY 2013
Interim

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
SENSORS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7320
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
January 2013	Technical Paper	15 September2008 – 19 July 2012

4. TITLE AND SUBTITLE
TUNABLE PHOTONIC MIRCROWAVE OSCILLATOR SELF-LOCKED BY POLARIZATION-ROTATED OPTICAL FEEDBACK (PREPRINT)

5a. CONTRACT NUMBER In-house
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 61102F

6. AUTHOR(S)
Nicholas G. Usechak and Vassilios Kovanis (AFRL/RYDH)
T.B. Simpson (L-3 Applied Technologies, Inc.)
Jia-Ming Liu and Mohammad AlMulla (University of California, Los Angeles)

5d. PROJECT NUMBER 2305
5e. TASK NUMBER DP
5f. WORK UNIT NUMBER Y05T

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Optoelectronic Technology Branch
Aerospace Components & Subsystems Division
Air Force Research Laboratory, Sensors Directorate
Wright-Patterson Air Force Base, OH 45433-7320
Air Force Materiel Command, United States Air Force

L-3 Applied Technologies, Inc.
University of California, Los Angeles

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RY-WP-TP-2013-0023

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory, Sensors Directorate
Wright-Patterson Air Force Base, OH 45433-7320
Air Force Materiel Command
United States Air Force

Air Force Office of Scientific Research (AFOSR)

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RYDH

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RY-WP-TP-2013-0023

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PAO Case Number 88ABW-2012-3102, Clearance Date 5 June 2012. Report contains color. Journal article to be published in Proc. IEEE International Frequency Control Symposium.

14. ABSTRACT
Combining optical injection and polarization-rotated optical feedback in a semiconductor laser can induce self-referenced periodic output that is widely tunable by simply varying the dc-bias points of the master and slave lasers. We observed feedback-induced reduction of the pulsation peak linewidth by more than two orders of magnitude relative to the injection-only case. The nonlinear dynamics of the optically injected semiconductor laser can be used to minimize sensitivity to fluctuations in the operating points. Performance is negatively affected by interference between the external injection signal and residual feedback in the same polarization.

15. SUBJECT TERMS
RF Oscillators, Tunable Oscillators, Injection Locking

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	8	Nicholas Usechak
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Tunable Photonic Microwave Oscillator Self-Locked by Polarization-Rotated Optical Feedback

T. B. Simpson
Pulse Sciences Division
L-3 Applied Technologies, Inc.
San Diego, CA, USA

Jia-Ming Liu and Mohammad AlMulla
Electrical Engineering Department
University of California, Los Angeles
Los Angeles, CA, USA

Nicholas Usechak and Vassilios Kovanis
Sensors Directorate
Air Force Research Laboratories
Wright-Patterson AFB, OH, USA
Vassilios.kovanis@wpafb.af.mil

***Abstract*—Combining optical injection and polarization-rotated optical feedback in a semiconductor laser can induce self-referenced periodic output that is widely tunable by simply varying the dc-bias points of the master and slave lasers. We observed feedback-induced reduction of the pulsation peak linewidth by more than two orders of magnitude relative to the injection-only case. The nonlinear dynamics of the optically injected semiconductor laser can be used to minimize sensitivity to fluctuations in the operating points. Performance is negatively affected by interference between the external injection signal and residual feedback in the same polarization.**

I. INTRODUCTION

The nonlinear dynamics induced via optical injection of a semiconductor laser offers a new path to improve the performance of low-noise photonic oscillators. Over a wide range of operating conditions, the injected optical signal perturbs the output of a slave laser so that it exhibits periodic dynamics instead of steady-state output. Simply by controlling the operating points of the master and slave lasers, through the bias currents, free-running offset frequencies, and injection power, the pulsation frequency can be widely tuned over the microwave and mm-wave bands [1]. When the optical output is detected by a conventional high-speed photodiode, the generated photocurrent reproduces the high-speed pulsation.

Fig. 1 shows a calculation of the pulsation frequency as a function of the amplitude and frequency detuning of the master laser signal [2]. The range of period-one (P1) dynamics is separated from stable locking by a Hopf Bifurcation, and it surrounds regions of more complex periodic and aperiodic/chaotic dynamics. The figure shows lines of constant pulsation frequency. Note that near the Hopf

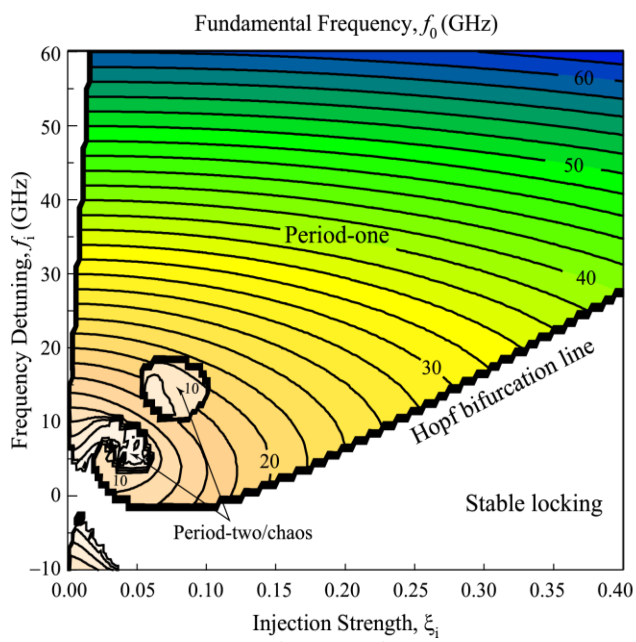

Figure 1. Calculated pulsation frequency of a semiconductor laser under optical injection as a function of the amplitude and detuning of the injected signal [2].

Bifurcation there are ranges where these lines are parallel to the detuning axis while for large positive offset currents they are essentially parallel to the injection amplitude axis. These conditions represent very different sensitivities to changes in the injection parameters.

Past work has demonstrated that optical injection can be used in combination with optoelectronic feedback for a novel photonic microwave oscillator [3]. When the optical injection induces the P1 pulsation, the feedback does not have to

T.B. Simpson and J.M. Liu were supported by AFRL under a contract with Optimetrics, Inc. Nicholas Usechak and Vassilios Kovanis were supported by the Air Force Office of Scientific Research.

provide the loop gain. It acts as the self-referencing input to narrow and stabilize the oscillation characteristics. Here, we combine optical injection with polarization-rotated optical feedback to demonstrate an all-photonic variation. The optical injection induces a P1 periodic pulsation in the output, with the nonlinear gain characteristic also acting as a narrowband microwave filter and feedback loop gain element. In a conventional semiconductor distributed feedback (DFB) laser the orthogonally polarized modes have very different profiles with very different resonance frequencies, and gain and loss characteristics. Rotating the polarization of part of the optical output and feeding it back into the slave laser along with the external injection effectively produces an optoelectronic feedback current which accompanies the optical injection, rather than a second optical injection into the oscillating mode. The feedback is now non-resonant with the optical cavity modes of the laser and primarily modifies the carrier density in the gain medium. This technique bypasses the losses, complexity, and amplifier 1/f-noise of the microwave circuit elements in a conventional optoelectronic oscillator (OEO) [4], while simultaneously being less sensitive to feedback pathlength fluctuations relative to conventional optical feedback techniques.

II. EXPERIMENTAL MEASUREMENTS

A. *Experimental Configuration*

Fig. 2 is a schematic of the experimental layout that uses an existing apparatus [5] with all optical components connected by single-mode, non-polarization-preserving fiber. The lasers are single-mode DFB lasers oscillating at approximately 1555.7 nm, and the free-running characteristics and nonlinear dynamics of the slave laser have been described previously [5]. The master laser is packaged with an optical isolator, and an optical circulator is used to further isolate the master laser from unwanted feedback. Both lasers are temperature stabilized and modulation currents can be added to the dc-bias currents of either the master or slave laser. The laser outputs are polarized, and fiber polarization rotators are used to adjust the polarization of the master laser to match that of the slave, and to rotate the polarization of the feedback signal to be orthogonal to the slave. The latter is accomplished by monitoring the output power spectrum of the slave laser without optical injection, and then adjusting the polarization of the feedback so that there is no evidence of external cavity modes. The slave laser output is monitored by an amplified fast photodiode and microwave spectrum analyzer. A third DFB laser is used as a tunable local oscillator. Sweeping the output frequency of this laser by varying the operating temperature and mixing with the slave laser output generates low-resolution (~100 MHz) optical spectra with the microwave spectrum analyzer.

B. *Operation with Polarization-Rotated Optical Feedback and Optoelectronic Feedback*

Fig. 3 shows the typical spectrum of the photodiode signal around the P1 pulsation frequency with and without polarization-rotated optical feedback. Without feedback, the spectrum consists of a single, fairly broad feature with a full-width half-maximum of approximately 2 MHz. The feedback causes multiple peaks to appear with a frequency separation determined by the roundtrip feedback delay time. This time could be adjusted by adding fiber patch chords into the delay path. To date, the "best" spectrum had a central peak about 15-20 dB stronger than the side peaks, with a detail shown in Fig. 4. The width of the peak, ~10 kHz and more than two orders of magnitude less than the external injection-only peak, was dominated by jitter. Also, the particular peak that formed the center of the feature hopped between 2-3 peaks. We observed that the amplitude of the injected optical signal fluctuated slowly in time and determined that this was due to interference between the injected master laser signal and the feedback signal. Therefore, in our apparatus there was residual feedback that remained in the original polarization at the point where the two optical signals were combined. The

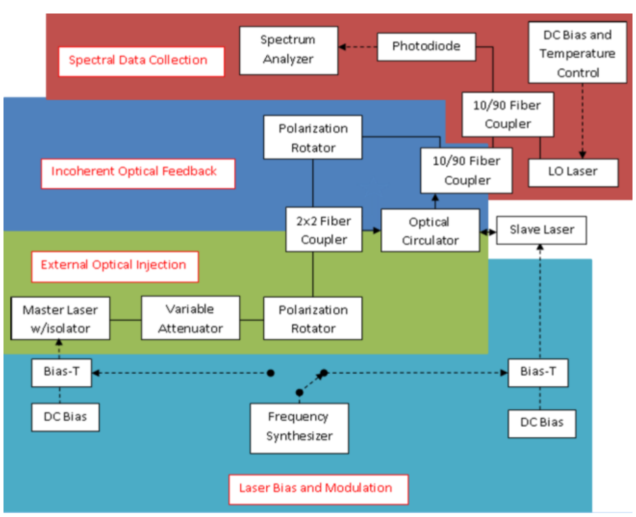

Figure 2. Schematic of the experimental apparatus.

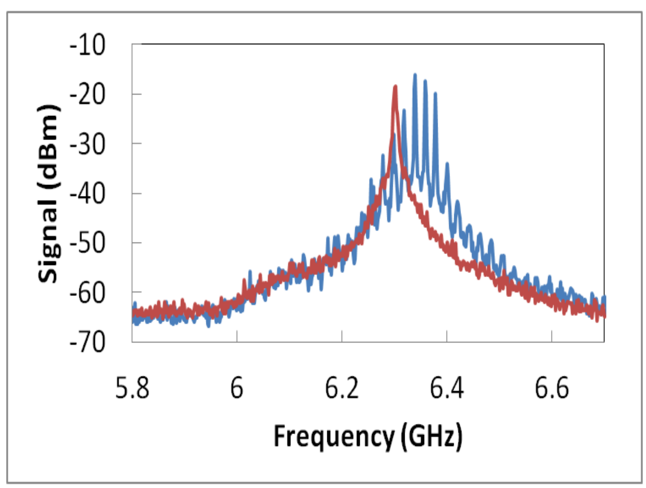

Figure 3. Power spectrum of the monitor photodiode signal under optical injection only (red – single peak), and with polarization-rotated feedback (blue – multiple peaks).

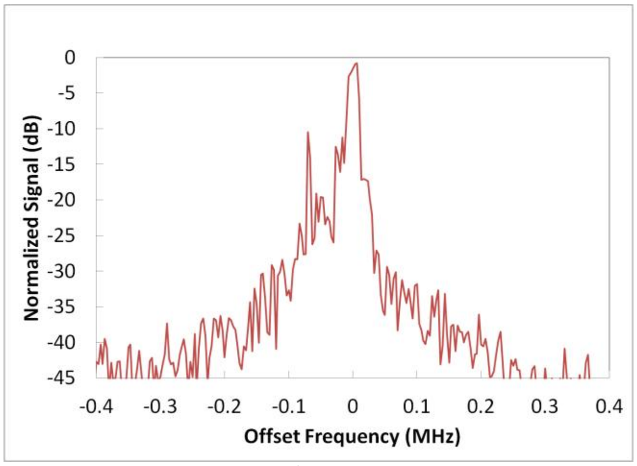

Figure 4. High resolution detail of the strongest peak under simultaneous optical injection and polarization-rotated optical feedback.

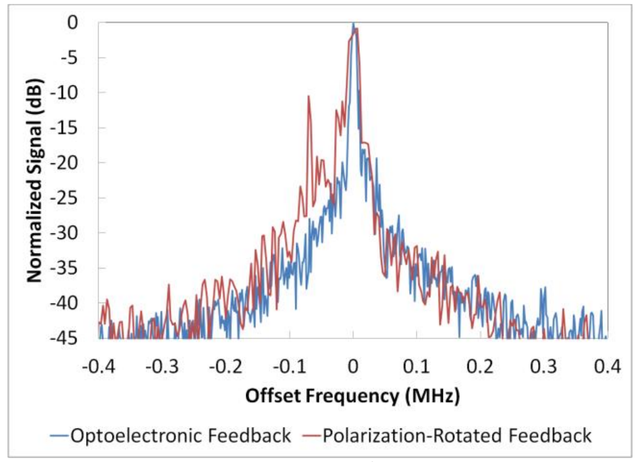

Figure 6. Higher resolution detail of the strongest peak under simultaneous optical injection and polarization-rotated feedback (red) or optoelectronic feedback (blue).

residual signal was enough to cause amplitude fluctuations of between 5-10%, though this depended on the specific injection amplitude of the master laser and feedback amplitude.

To determine the relative importance of the residual feedback coherently interfering with the injected signal from the master laser, we substituted optoelectronic feedback for the polarization rotated feedback. A second fast photodiode (not shown in Figure 2) was used to convert the optical output from the slave laser into a modulation current that was fed back to the slave laser along with the DC bias through the bias tee. Fig. 5 shows the resulting spectrum of the laser under simultaneous optical injection and optoelectronic feedback. Shown in Fig. 6 for direct comparison are the central peak of the optically-injected laser with optoelectronic feedback and the same optically-injected laser with polarization-rotated optical. The former peak in Fig. 6 was distinctly narrower, though jitter continued to dominate the spectral width, and the hopping between peaks was similar.

C. Operating Points with Reduced Fluctuation Sensivity

The jitter could be due to relative fluctuations in the operating points of the two lasers. By making use of the varying nonlinear dynamics, we were able to isolate the key source of jitter as amplitude fluctuations of the injected signal from the master laser into the oscillating mode of the slave laser. Recalling Fig. 1, there are operating points where the pulsation frequency is insensitive to changes in the detuning of the master laser. By observing changes in the amplitude of a modulation current added to the slave laser, we found that these points were also points of relative insensitivity to slave laser current fluctuations. Fig. 7 shows the pulsation frequency characteristics, around one of these operating points, along with a plot of the amplitude of sidebands induced on the pulsation peak by current modulations with a frequency between 50-500 MHz. The sidebands disappeared at the operating points where the pulsation frequency went through a local minimum. Therefore, the pulsation peak is simultaneously insensitive to relative frequency fluctuations of the master and slave laser and amplitude fluctuations of the slave laser. Only amplitude fluctuations of the injected optical signal remain.

D. High-Frequency Operation

At higher pulsation frequencies, beyond the 8-GHz bandwidth of the photodiodes used in this experiment, we observed superior performance of the polarization-rotated

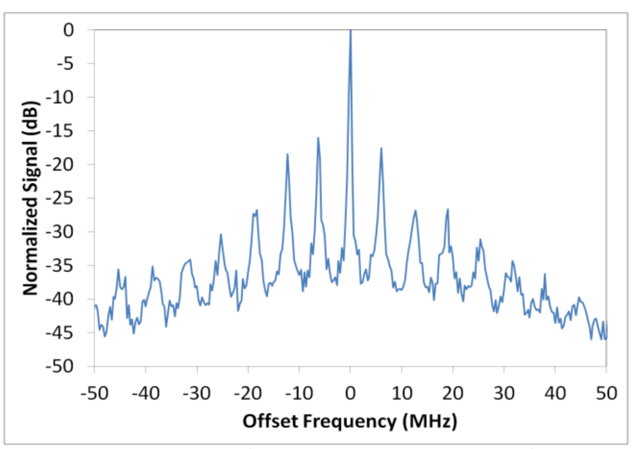

Figure 5. Power spectrum of the monitor photodiode signal for the laser under simultaneous optical injection and optoelectronic feedback.

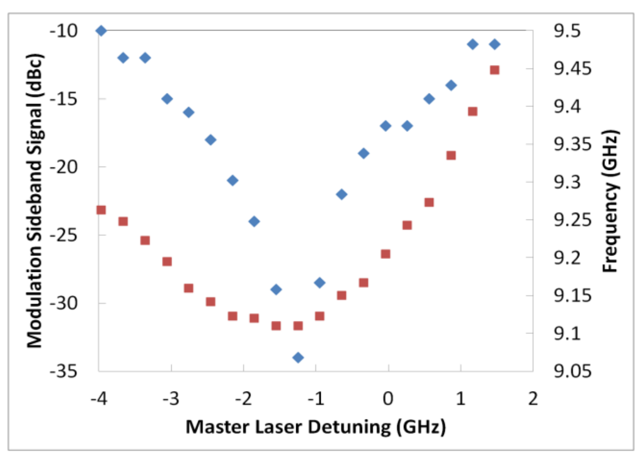

Figure 7. Pulsation frequency as a function of detuning of the master laser (squares) and strength of sidebands on the pulsation peak due to current modulation of the slave laser at 100 MHz (diamonds).

optical feedback relative to the optoelectronic feedback. Fig. 8 shows the relative performance of the polarization-rotated optical feedback compared to the optoelectronic feedback when the pulsation frequency is increased to nearly 20 GHz. The shift in the polarization-rotated peak is due to drift during the experiment. While superior to the optoelectronic feedback when circuit losses become important, the polarization-rotated optical feedback is not as effective at the higher frequencies as it is at lower frequencies.

III. Analysis

The drop in effectiveness of polarization-rotated optical feedback in reducing the P1 pulsation linewidth at high optical frequencies can be understood by examining the coupled-equation model for the circulating field amplitude and carrier density. This model has been successfully used to model the nonlinear dynamics of the optically injected semiconductor laser [1,5]. If we assume that the optical spectrum is dominated by two strong optical frequency components for larger pulsation frequencies, as has been previously observed, then the resulting leading order terms for the normalized optical field, $(1+a)e^{i\varphi}$, and carrier density, $\tilde{n}$, can be cast in the form:

$$(1+a)e^{i\varphi} \approx a_0 e^{i\varphi_0} + a_1 e^{i(\Omega\tau_1+\varphi_1)} \tag{1}$$

$$\tilde{n} \approx \frac{\gamma_s \tilde{J}}{\gamma_n}\left(\frac{1-\left(a_0^2+a_1^2\right)}{\frac{\gamma_s}{\gamma_n}+\left(a_0^2+a_1^2\right)} + 2a_0 a_1 \frac{\gamma_n}{\Omega_1}\sin\left(\Omega_1\tau+\varphi_1-\varphi_0\right) + O\left(\frac{\gamma_n}{\Omega_1}\right)^2 \right) \tag{2}$$

where the normalization is with respect to the free-running values, Ω_1 is the pulsation frequency, γ_s is the carrier decay rate, γ_n is the differential gain rate, and $\tilde{J}$ is the normalized pump parameter, which is the difference between the slave laser bias current and threshold current, divided by the threshold current. We are taking as the smallness parameter, γ_n/Ω_1, with the observation that the solutions of interest have Ω_1 equal to or greater than the free-running relaxation resonance frequency, which is typically much larger than the differential gain rate. The key point is that the pulsation term in the carrier equation scales with the smallness parameter. As Ω_1 increases, the pulsation has a weaker influence on the carrier density, and thus there is a weaker coupling of the polarization-rotated optical feedback to the laser mode.

This analysis is further supported by numerical calculations of the full nonlinear coupled equations. Fig. 9 shows the dependence of the pulsation frequency, $f_0 = \Omega_1/2\pi$, and the amplitude of the pulsation on the detuning of the master laser for a fixed injection amplitude. As the frequency increases, the amplitude of the modulation decreases due to the decreased response of the carriers in the gain medium.

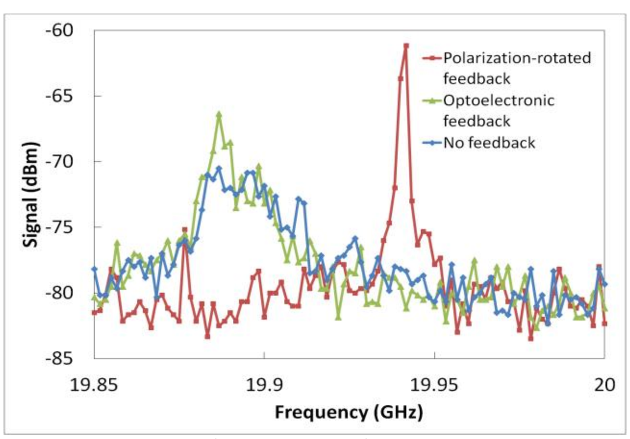

Figure 8. Comparison of the narrowing of the jitter-dominated pulsation at higher frequencies by optoelectronic and polarization-rotated optical feedback.

IV. Conclusions

In conclusion, polarization-rotated optical feedback provides a self-referencing signal to stabilize the tunable pulsations of a semiconductor laser subject to external optical injection. Nonlinear dynamics generate operating conditions where the P1 pulsation frequency exhibits reduced sensitivity to fluctuations of master and slave laser operating points. Residual optical feedback in the original polarization induces amplitude jitter due to interferometric effects with master laser injection in our fiber-coupled system. Investigations are underway to control these fluctuations and improve performance.

References

[1] T.B. Simpson, J.M. Liu, A. Gavrielides, V. Kovanis, and P.M. Alsing, "Period-doubling cascades and chaos in asemiconductor laser with optical injection," Phys. Rev. A, vol. 51, pp. 4181-4185, 1995.

[2] S.C. Chan, S.K. Hwang, and J.M. Liu, "Period-one oscillation for photonic microwave transmission using an optically-injected

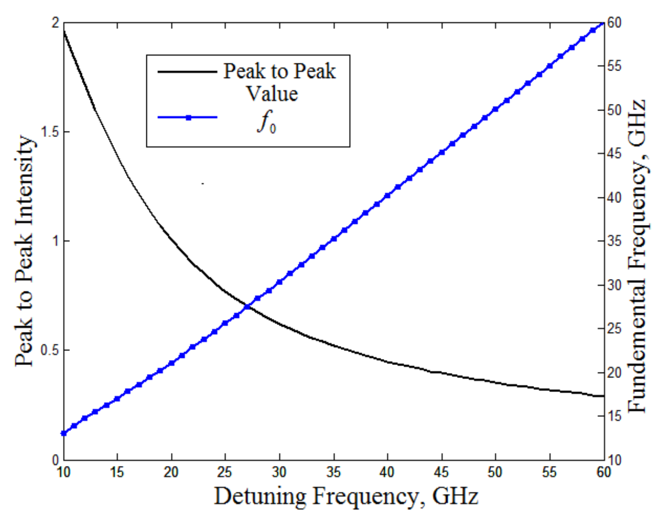

Figure 9. Calculated dependence of the pulsation frequency, f_0, and the amplitude of the pulsation on the detuning frequency of the master laser for a fixed injection amplitude.

semiconductor laser," Optics Express, vol. 15, pp. 14921-14935, 2007.

[3] S.C. Chan and J.M. Liu, "Tunable narrow-linewidth photonic microwave generation using semiconductor laser dynamics," IEEE J. Select. Topics Quantum Electron., vol. 10, pp. 1025-1032, 2004.

[4] D. Eliyahu, D. Seidel, and L. Maleki, "RF amplitude and phase-noise reduction of an optical link and an opto-electronic oscillator," IEEE Trans Microwave Theory Tech., vol. 56, pp. 449-456, 2008.

[5] T.B. Simpson, "Mapping the nonlinear dynamics of a distributed feedback semiconductor laser subject to external optical injection," Opt. Commun., vol. 215, pp. 135-151, 2003.