# Discriminator-Aided Optical Phase-Lock Loop Incorporating a Frequency Down-Conversion Module

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***Abstract*—A new discriminator-aided optical phase-lock loop (OPLL) incorporating a frequency down-conversion module to generate a low phase noise, highly frequency-stable, and frequency-tunable microwave signal is proposed and demonstrated. The inclusion of the frequency down-conversion module allows the use of lower frequency components in the control circuits with a reduced cost. In addition, the new design allows continuous frequency tuning of the generated microwave signal. The down-conversion concept is presented, along with a phase noise analysis detailing the contributions to the phase noise from the reference sources. An OPLL based on the proposed configuration is implemented. The phase noise performance, as well as the frequency stability is experimentally studied.**

***Index Terms*—Frequency down-conversion, frequency discriminator, optical heterodyning, phase-lock loop.**

## I. INTRODUCTION

A LOW PHASE NOISE, highly frequency stable, and frequency tunable microwave or millimeter-wave (mm-wave) source is desirable for many modern applications such as radar, satellite communications, broadband wireless access networks, and broadband sensor networks. The distribution of a microwave or mm-wave signal in the electrical domain is not practical due to the prohibitively high loss associated with electrical distribution lines, such as coaxial cable. Thanks to the extremely broad bandwidth and low loss of state-of-the-art optical fiber, the distribution of microwave or mm-wave signals over optical fiber, or radio-over-fiber (RoF), is an ideal technique to fulfill this requirement. The ability to generate a microwave or mm-wave signal in the optical domain would allow the distribution of the signal via optical fiber from a central office to a remote site, greatly simplifying the equipment requirement at the remote site.

One method to optically generate microwave or mm-wave signals is to use optical heterodyning—a process where two optical waves of different wavelengths beat at a photodetector in order to generate a microwave or mm-wave output [1]. This solution is capable of generating frequencies potentially into the terahertz (THz) band, limited only by the bandwidth of the photodetector.

One method of optical heterodyning to generate low phase noise microwave or mm-wave signals is to use an optical phase-lock loop (OPLL). This technique has been explored extensively [2]–[6]. The OPLL is a dual wavelength source which uses an electrical phase-lock loop to maintain a fixed phase relationship between the two wavelengths, with a wavelength spacing corresponding to the desired microwave or mm-wave frequency.

In an OPLL configuration, in addition to a phase-lock loop, one may also add a frequency discriminator, to reduce the frequency fluctuations, as was reported in [6]. However, the discriminator-aided OPLL system in [6] suffers from some limiting constraints. First, the electrical mixer, amplifiers, and power dividers used must be capable of operating up to the desired output frequency. The reference source used in the phase-lock loop must also operate at the output frequency. Second, the frequency discriminator, which is a delay line filter, is limited to operate at discrete points, the spacing of which is defined by the length of the delay line in the filter. This excludes the possibility of continuous tuning of the microwave output frequency. In this letter, we propose a new and unique modification to the feedback circuit that will overcome these limitations.

## II. DESIGN AND ANALYSIS

### A. OPLL

The new OPLL configuration is shown in Fig. 1. A frequency down-conversion module that consists of a high-frequency reference source S1 and an electrical mixer M1 is added to the system after the photodetector. The frequency down-converted signal is then split by a power divider, with one part being sent to the frequency discriminator, and the other sent to a phase detector, which consists of a low-frequency reference source S2, an electrical mixer M3, and a low-pass filter LP1. The output of the phase detector is used to control the phase of the slave laser to phase-lock it to the master laser diode.

In this new configuration, to generate a microwave signal at 11.2 GHz, S1 is chosen to operate at 12 GHz, so that the frequency discriminator now operates at the offset frequency of these two, which is 800 MHz. The discriminator, a two-tap delay line filter, is designed by controlling the delay line length such that is has an operating null at 800 MHz. A DC feedback proportional to the difference between the down-converted frequency and the 800-MHz null is generated and sent to the master laser to maintain a fixed wavelength difference corresponding to 11.2 GHz.

Once the two laser diodes are frequency-locked, the phase detector circuit is engaged with S2 tuned to the same operating frequency as the discriminator. Operating at this lower frequency

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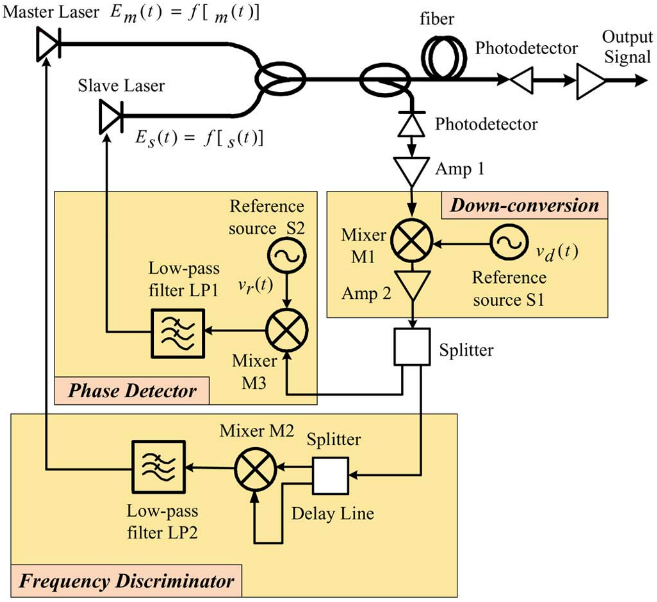


Fig. 1. Discriminator-aided OPLL with a frequency down-conversion module. (Color version available online at http://ieeexplore.ieee.org.)

allows the use of low-frequency components for the phase detector and the frequency discriminator that are readily available at very low cost. Another benefit offered by this design is the ability to continuously tune the microwave frequency. In the new arrangement, by simply changing the frequency of S1, the frequency discriminator and the phase detector would work together to change the wavelength spacing between the two laser diodes to maintain the fixed frequency of 800 MHz at the output of the frequency down-conversion module.

### *B. Phase Noise Analysis*

The additional phase noise contribution of the reference source S1 can be determined following a similar analysis, as in [4]. It is assumed that the master and slave lasers have been phase-locked and that the phase error is sufficiently small to allow linearization of the system. It is also assumed that the frequency discriminator does not contribute to the phase noise at the output. This assumption is justified by the fact that the frequency discriminator is designed to act only on the frequency error between the incoming signal and its set point and does not respond to the more quickly varying phase error [7]. Also, once the system is phase-locked, the frequency is highly stable, under this condition, the discriminator design indicates that its output is practically zero, and therefore will not affect the beat signal.

Under these assumptions, the phase difference between the master and slave laser diodes, and the phase error at the output of the phase detector are, respectively

$$\phi_{ms}(t) = \phi_{mo} - \phi_{so} + \gamma_m(t) - \gamma_s(t) \tag{1}$$

$$\theta(t) = \phi_{mo} - \phi_{so} - \phi_r(t) - \phi_d(t) + \gamma_m(t) - \gamma_s(t) \tag{2}$$

where $\phi_{mo}$ and $\phi_{so}$ are the quiescent phases, $\gamma_m(t)$ and $\gamma_s(t)$ are the phase fluctuations of the master and slave lasers, respectively, and $\phi_d(t)$ and $\phi_r(t)$ are the phase noise contributions from the high-frequency reference source S1 and low-frequency reference source S2, respectively.

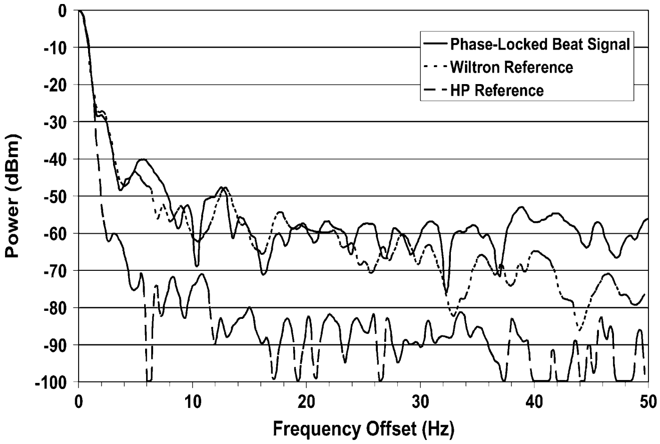


Fig. 2. Electrical spectra of the OPLL beat signal and the two reference sources.

Using these expressions, the Laplace transforms of the instantaneous values of $\phi_{ms}(t)$ and $\theta(t)$ are

$$\begin{aligned}\phi_{ms}(s) = [1 - H(s)][\Gamma_m(s) - \Gamma_s(s)] - H(s)[N'(s)\\ - (\phi_d(s) + \phi_r(s))]\end{aligned} \tag{3}$$

$$\begin{aligned}\theta(s) = [1 - H(s)][\Gamma_m(s) - \Gamma_s(s) - (\phi_d(s) + \phi_r(s))]\\ - H(s)N'(s)\end{aligned} \tag{4}$$

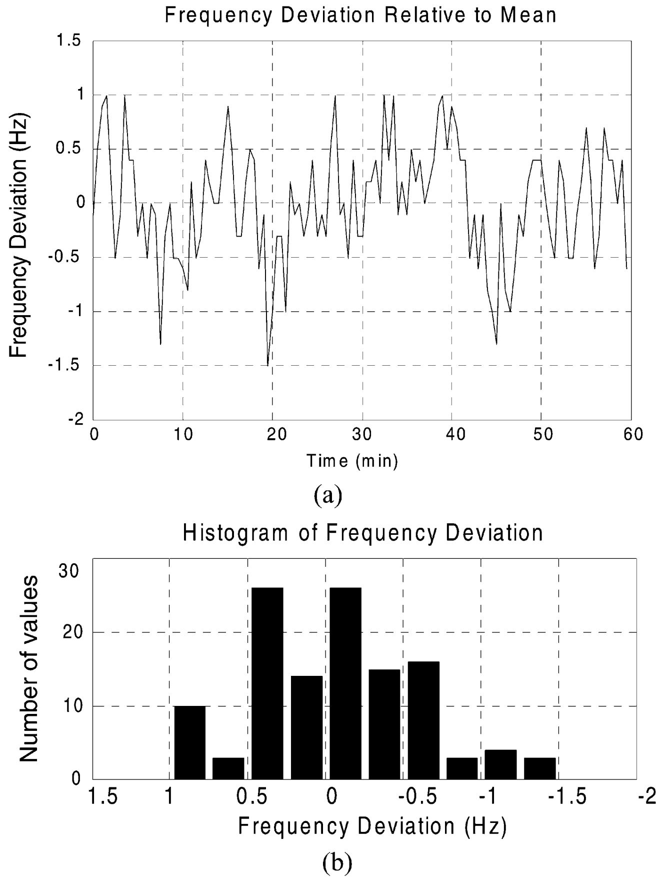
where $\Gamma_m(s), \Gamma_s(s)$, and $N'(s)$ are the Laplace transforms of $\gamma_m(t), \gamma_s(t)$, and $n'(t)$ (the photodetector shot noise) [4], respectively, and $H(s)$ is the closed-loop transfer function of the OPLL with the down-conversion stage.

From (3) and (4), we see that the S1 phase term combines additively with the S2 phase term. The inclusion of the down-conversion module results in an increase in the phase noise level corresponding to the magnitude of S1's phase noise [8], [9]. Even though this additional phase noise affects the phase noise performance of the overall system, if S1 is of high quality, its impact on the overall system phase noise will be minimal, while still bringing the other benefits of the down-conversion setup described above.

## III. RESULTS

The following section provides the experimental results for the phase noise measurement carried out on the system, as well as plots to show the beat signal quality and the system frequency stability.

The phase noise is measured using an Agilent E5052A Signal Source Analyzer when the two lasers are phase-locked. These measurements are carried out at a loop operation frequency of 11.2 GHz, which corresponds to a wavelength spacing of about 90 pm. The resultant phase noise is measured to be −64.7 dBc/Hz at 100 Hz offset and −72.5 dBc/Hz at 10 kHz offset. The output signal spectrum is measured using an Agilent 8565E Spectrum Analyzer (9 kHz–50 GHz). The result is shown in Fig. 2. The figure also shows the spectra of the high-frequency reference source S1 (Wiltron 69387A), and the low-frequency source S2 (HP8648D). The quality of



(a)

(b)

Fig. 3. Frequency deviation measurement of the OPLL output over a 60-min time period. Measurements were taken every 30 s. (a) Frequency deviation. (b) Histogram of the frequency deviation.

the phase-locked signal closely matches the quality of the reference sources. The 3-dB bandwidths of the signals can all be seen to be about 1 Hz, which is the resolution bandwidth of the spectrum analyzer. The noise level of the beat signal is slightly higher than either of the two reference sources. This is consistent with the analysis carried out in Section II-B.

A frequency stability analysis of the output signal is also performed. A one-hour measurement is carried out with trace data taken every 30 s. The frequency value of the signal peak is then extracted and the trend over the 60-min period is plotted. The result is shown in Fig. 3. It can be seen that the output signal is highly frequency stable with maximum deviation of no more than 1.5 Hz over the time period, as shown in Fig. 3(a). The histogram plot of the stability data in Fig. 3(b) shows an almost Gaussian distribution of the peak frequency about the mean during this period. Further trials over longer intervals are required to confirm this distribution. A measurement of the reference sources is also done in this manner and a similar frequency deviation is seen in their output. Thus, it appears that the output signal follows the deviations seen in the reference sources.

## IV. CONCLUSION

We have presented and experimentally demonstrated a new discriminator-aided OPLL incorporating a frequency down-conversion module to reduce the feedback frequency. This technique offers the advantages of permitting the use of lower frequency components for the phase detector and the frequency discriminator, as well as allowing the output microwave frequency to be continuously tunable. An analysis of this new arrangement was conducted which showed that the high-frequency reference source used in the frequency down-conversion module would contribute an additive phase-noise term to the overall phase noise of the generated microwave signal. Experiments were carried out to study the performance of the OPLL. The results showed that the phase noise and frequency stability of the generated microwave beat signal closely matched those of the reference sources.

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