Electronic Stabilization Methods for a Single-Loop Opto-Electronic Oscillator

Mehmet Alp Ilgaz, Luka Bogataj, Boštjan Batagelj, Matjaž Vidmar

University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia

mehmet.ilgaz@fe.uni-lj.si

Abstract—The opto-electronic oscillator (OEO) is an oscillator with an optical delay line as a resonator. The fact that the increase in frequency of an OEO does not increase its phase noise is an important advantage. This enables the generation of low phase-noise signals in the microwave and millimeter wave regions. However, for its more widespread use two problems must be dealt with: frequency drift and multi-mode oscillation. This paper presents recently proposed, novel methods that address the frequency drift and the OEO's multi-mode nature. By implementing a feedback control loop into the OEO it is possible to achieve a frequency drift of 0.05 ppm/K. With an additional phase modulation of the OEO's loop it is possible to increase the side-mode suppression ratio (SMSR) by 5 dB, and a 20-dB improvement in the SMSR is possible with a quality multiplier. The suggested methods operate in the electrical domain, which makes them simple, accessible and low cost.

Index Terms—*opto-electronic oscillator, microwave photonics, long-term stability, multi-mode operation, phase noise, feedback control loop, additional phase modulation, quality multiplier.*

I. INTRODUCTION

The opto-electronic oscillator (OEO), shown in Fig.1, was invented in the mid-1990s. It consists of an optical part, which generates large delay time, and an electrical part, which is the feedback [1]. An optical delay line serves as a high-quality-factor resonator. One of the advantages of an OEO is that it can generate optical and microwave outputs simultaneously [2], as shown in Fig. 1. Radio-over-fiber technology could benefit from this possibility because there is no need for an additional conversion [3].

In various types of high-frequency oscillators the problem is that the phase noise is increasing with the frequency because of the resonator's properties. The quality factor of a delay line in an OEO is frequency dependent, which makes the phase noise frequency independent. On the other hand, the OEO has problems such as frequency drift and multi-modes. These should be dealt with in order to allow the system to work efficiently.

The frequency drift is a result of the refractive-index's temperature coefficient. Because the OEO's frequency depends on its loop's group delay, every change in the refractive index affects its frequency. The temperature coefficient of the OEO's frequency is 8 ppm/K for a standard single-mode fiber [4].

Different methods to lower the temperature coefficient are proposed in the literature. The optical fiber and the bandpass filter can be temperature stabilized [4], the monitoring signal can be implemented [5] or special building blocks can be used [6]. All these methods stabilize a specific building block or the method needs an additional stable signal to measure the delay. We therefore proposed a method that uses a feedback control loop to stabilize the frequency [7]. With this method there is no need for any bulky fiber stabilization or additional signals.
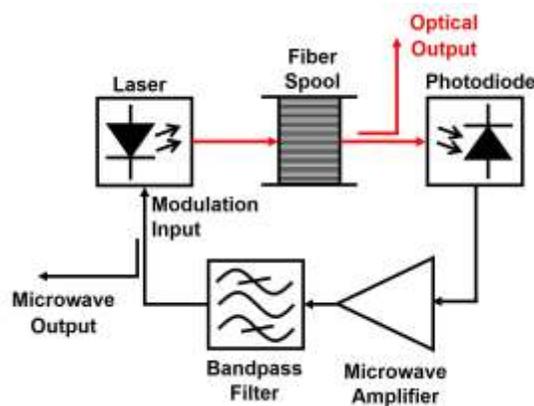

Fig. 1. Schematic of a single-loop OEO.

As shown in Fig. 1, the bandpass filter is located in the OEO's loop. The purpose of a bandpass filter is to choose the mode at which the oscillator will operate [8]. Since the filter's bandwidth is not infinitely narrow, the spectrum of the oscillator's signal still includes other modes. In the single side-band phase-noise spectrum, side modes are shown as unwanted spurious peaks. To reduce the power of side modes, a multi-loop OEO configuration can be implemented [9-11], injection locking between two OEOs can be used [12], ultrahigh-Q whispering gallery mode resonator can be placed in the OEO loop [13] or a very narrow bandpass filter can be implemented [14], as well as other methods.

To ensure the high side-mode suppression ratio (SMSR) of a single-loop OEO we proposed two different methods. One method uses an additional phase modulation of the oscillator's loop to increase the SMSR [15]. The other method decreases the loop's bandwidth with a quality multiplier, which is added to the bandpass filter [16].

All three methods are presented into detail elsewhere [7], [15], [16]. In this paper the basic principle of operation is given for all three methods in Section II, where the results are also presented. In Section III a comparison with different methods is shown and future developments are suggested.

II. Electronic stabilization methods

A method with a feedback control loop stabilizes the OEO's frequency. To increase the SMSR, additional phase modulation and a quality multiplier are proposed.

All three methods were developed for an OEO that is operated at 3 GHz. The optical delay line consisted of a directly modulated, semiconductor, distributed-feedback laser with a wavelength of 1550 nm, 15-km of G.652D optical fiber and an InGaAs p-i-n photodiode. A bandpass filter with a quality factor of 8300 was used. Commercial monolithic microwave integrated circuits (MMICs) were used as amplifiers. The free spectral range (FSR) was approximately 13 kHz [7], [15], [16].

A. Feedback Control Loop

For long-term frequency stabilization, a feedback control loop was proposed [7]. Figure 2 shows the basic operating principle for an OEO with a feedback control loop. As shown in Fig. 2, the feedback control loop includes a frequency discriminator and a laser temperature control.
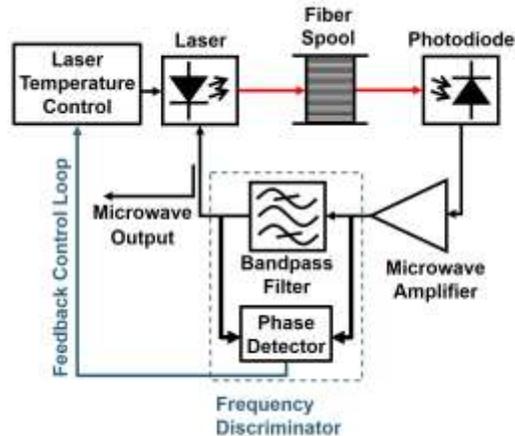

Fig. 2. Schematic of an OEO with a feedback control loop.

The frequency discriminator measures the OEO's frequency. The information about the frequency is then led to a laser temperature control, where the proportional-integral controller changes the laser's temperature. The latter is changed in such a way that the frequency discriminator's output has a constant value. In this way the OEO's frequency is stabilized compared to an OEO without any feedback control loop. Using this method, a coefficient of 0.05 ppm/K was achieved [15]. This result is shown in Fig. 3.

A feedback control loop keeps the frequency constant, because it makes the group delay of the oscillator's loop constant. The group delay of the OEO's loop depends on factors such as the refractive index and amplifier's phase shift. If the group delay changes, the control loop will compensate for this change with a changed refractive index. As a result, the group delay, and therefore the frequency, will remain constant. The refractive index is manipulated with a change in the wavelength of the light. This is possible because of the chromatic dispersion [7]. The wavelength of the light was manipulated with the laser's temperature [7].

Besides the long-term frequency stability, the phase noise was also measured for two different configurations: an OEO with a feedback control loop and an OEO without a feedback control loop [15]. The results are shown in Fig. 4. It is clear that the feedback control loop does not affect the phase-noise performance of an OEO. The two curves in Fig. 4 overlap.
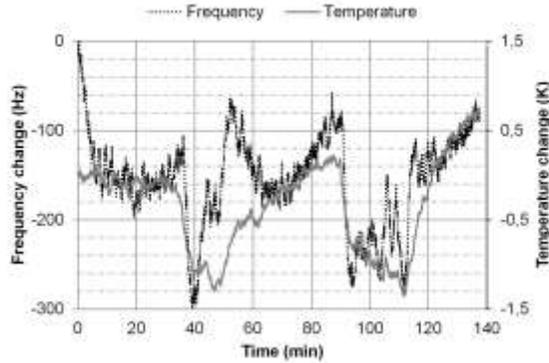

Fig. 3. Frequency change of an OEO during a measurement interval of 140 minutes. Frequency drift is approximately 150 Hz/K (0.05 ppm/K).
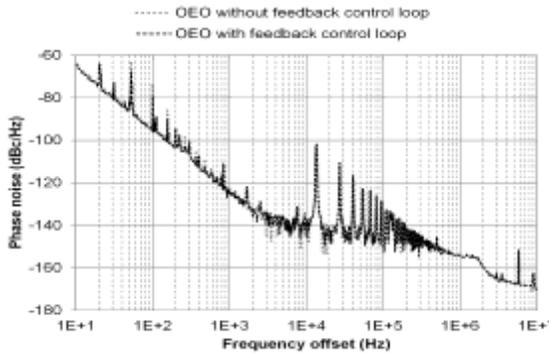

Fig. 4. Phase noise for an OEO with and without a feedback control loop. It is clear that the feedback control loop does not affect the phase-noise performance.

B. Additional Phase Modulation

Fig. 4 shows unwanted peaks at frequency offsets over 10 kHz. This is due to the OEO's multi-mode nature of oscillation. In order to eliminate these unwanted modes (spurious peaks), a method with an additional phase modulation was proposed [15]. This technique is shown in Fig. 5.

With this method an electrically controlled phase shifter (ECPS) is placed in the OEO loop. The ECPS is controlled by a signal with a frequency that has the same value as the FSR of a constructed OEO. This frequency is obtained with the frequency mixing of the filter's input and output signals, as shown in Fig. 5. The obtained signal is then led through the *SMSR booster* circuit to an ECPS [15]. The purpose of a *SMSR booster* is to provide a suitable amplitude and phase to the signal that drives the ECPS. If the amplitude and phase are chosen correctly (tuning), the OEO's SMSR will increase.

Fig. 6 shows the results of phase-noise measurements. Fig. 6 (a) shows a phase-noise spectrum. There are three regions where additional phase modulation affects the phase noise performance. The power of the side modes is decreased. This part is encircled in Fig. 6 (a), with the detail shown in Fig. 6 (b). A 5-dB increase in the SMSR was reported [15]. The two black arrows in Fig. 6 (a) mark regions where the phase noise increases because of an additional phase modulation. In the close-in region there is a small increase of 1 dB. At a 1-MHz offset there is also an increase of the phase noise.
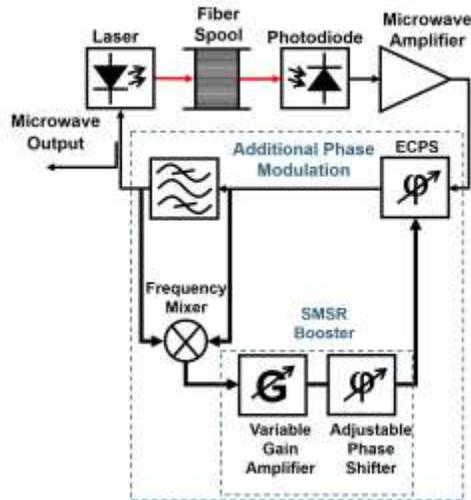
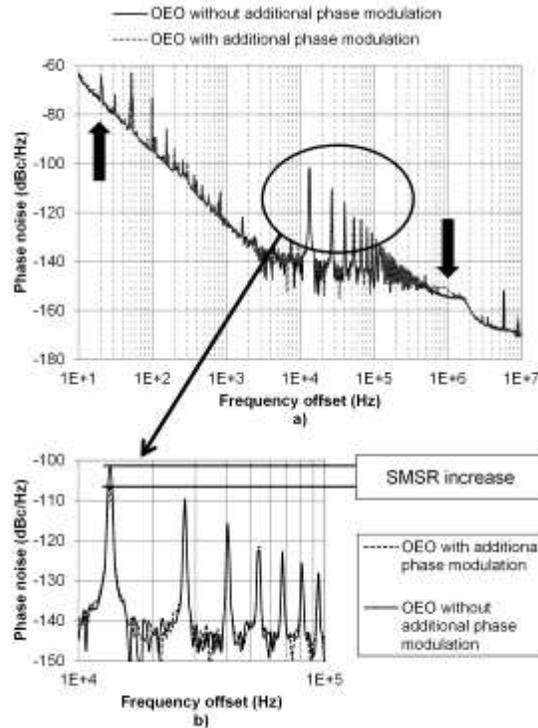Fig. 5. Schematic of a single-loop OEO with additional phase modulation.

Fig. 6. Phase noise measurements of an OEO with additional phase modulation. a) Comparison of the phase-noise spectrum of an OEO with and without additional phase modulation. Additional phase modulation has a minimal impact on the phase noise but it increases the SMSR. b) Detail of side modes in phase-noise spectrum. 5-dB increase in the SMSR was reported.

C. Quality Multiplier

Another technique to increase the SMSR of an OEO, presented recently, is the addition of a quality multiplier to a bandpass filter in an OEO loop [16]. In this technique a microwave electrical circuit is added to a bandpass filter in order to decrease the bandwidth of the OEO loop. A schematic of an OEO with a quality multiplier is shown in Fig. 7. If the loop bandwidth is decreased, the SMSR of the OEO will increase [9].

To decrease the loop bandwidth, a positive feedback is added to the bandpass filter. If the open loop gain of the filter with a quality multiplier (FQM) is lower than unity and the phase shift of the FQM's open loop is equal to 2π, the FQM operates as a filter with a narrower bandwidth and a lower insertion loss compared to a bandpass filter on its own [16].

Measurements of the phase noise for an OEO with a quality multiplier are shown in Fig. 8. The phase noise for an OEO without a quality multiplier is also shown. It is clear that the improvement in the SMSR is almost 20 dB. As a side effect, the phase noise increases by 4 dB at 1-kHz offset. In this case the bandwidth of the FQM was eight times narrower than the bandwidth of the filter on its own: 45 kHz.
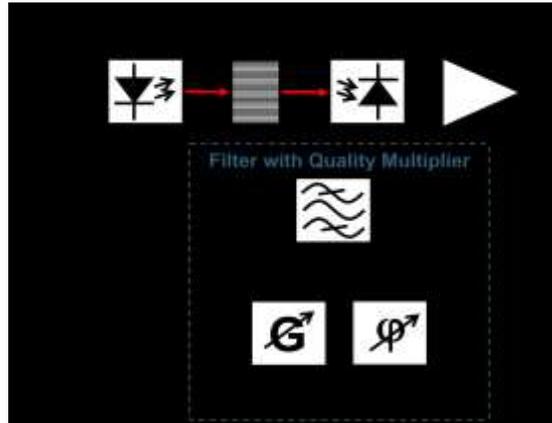

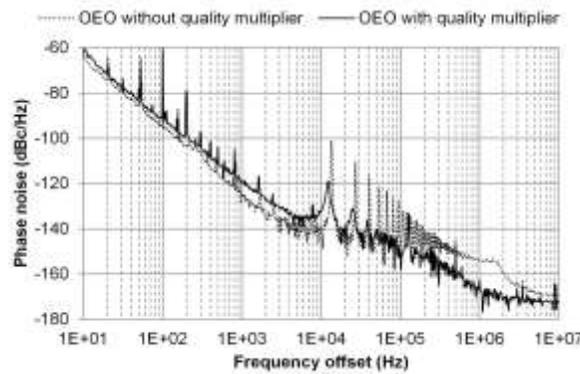Fig. 7. Schematic of a single-loop OEO with quality multiplier.

Fig. 8. Comparison of phase noise for OEOs with and without quality multiplier.

III. CONCLUSION

Three methods for OEO stabilization were presented here as a review of our previous work [7], [15], [16]. With a feedback control loop a frequency temperature coefficient of 0.05 ppm/K was achieved. With additional phase modulation a 5-dB increase was reported. An OEO with a quality multiplier had a SMSR that was 20-dB higher than for an OEO without a quality multiplier.

The method with a feedback control loop can be compared with an OEO where the optical fiber and bandpass filter are temperature stabilized [4]. The authors of [4] achieved a frequency temperature coefficient of 0.1 ppm/K. This was improved by a factor of 2 with a feedback control loop. There was no need for any temperature stabilization of the optical fiber. The latter may still be needed because of the laser's temperature range [7]. To further improve the reported results for a feedback control-loop method, a more precise temperature stabilization of the frequency discriminator should be implemented.

A method with additional phase modulation managed to improve the SMSR by 5 dB, which is lower than other methods, such as a multi-loop OEO [9-11] or injection-locked dual OEO [12]. It is believed that the SMSR can be improved by lowering the noise density in the SMSR booster and the frequency-mixer circuits [15]. This method can be appropriate for implementation in an integrated circuit because of the simple and low-frequency electrical circuits.

A major advantage of an OEO with a quality multiplier is its simple construction compared to other methods for a SMSR increase. An injection-locked dual OEO has twice as many components as a single-loop OEO [12]. A multi-loop OEO has one or more additional optical delay lines [9-11]. An OEO where a Fabry-Perot etalon is used as a filter uses a highly specialized component [14]. Further tests at higher frequencies are necessary in the future.

Our future work will also focus on an evaluation and exploration of electronic techniques for the stabilization of a single-loop opto-electronic oscillator at higher frequencies. The question of influence between those three methods is a priority for further investigations. The evidence from our preliminary experiments shows promising results. Our aim in developing the OEO is to provide stable and pure microwaves as well as optical signals that will enable future 5G networks. An important part of our strategy for achieving this is to recognize that in future 5G networks the use of an OEO may serve as a tool for enabling high bandwidth and low latency.

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