Opto-Electronic Oscillators

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An opto-electronic oscillator (OEO) is one of the most popular types of oscillators for generating micro- and millimeter wave signals.

opto-electronic oscillator | phase noise | microwave signal | millimeter wave signal

1. Introduction

High-precision signal oscillators are needed in a variety of fields such as satellite communications, optical communications, radar applications, radio-over-fiber communications, etc. [1]. In its most basic form, an oscillator consists of a resonator and a feedback component. When the Barkhausen conditions are satisfied, the oscillator starts generating the fundamental oscillation signal. An opto-electronic oscillator (OEO) is one of the most popular types of oscillators for generating micro- and millimeter wave signals [2][3]. The OEO has a number of optical components such as a laser diode [4][5], an optical fiber [6] and a photodiode [7]. The electrical components including an electrical bandpass filter and an electrical amplifier are used to complete the feedback loop. The laser of the OEO can be modulated directly, or it can use external modulation with an electro-optic modulator such as a Mach Zehnder modulator (MZM) [8] or an electro-absorption modulator [9]. A typical externally modulated OEO is shown in Figure 1.

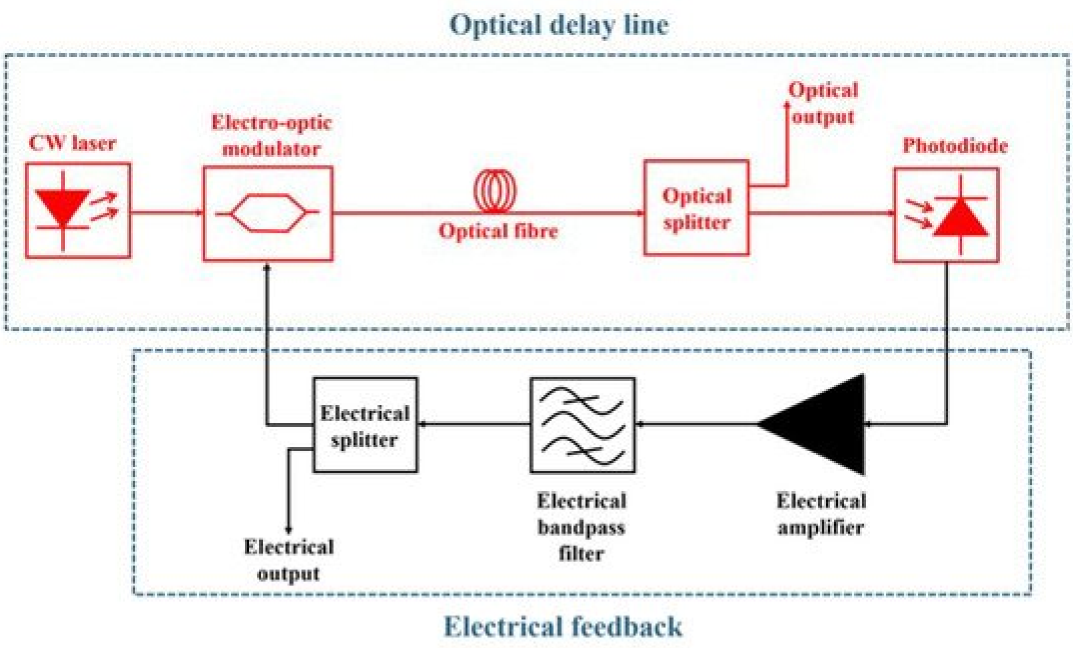

Figure 1. Single-loop opto-electronic oscillator (OEO) with electrical components.

Currently, −163 dBc/Hz at a 6 kHz offset from the carrier for an operating frequency of 10 GHz [10] is the lowest phase noise achieved so far. Different types of configurations for the OEO have already been presented in the literature. The dual-loop and multi-loop configurations [11][12][13][14], coupled OEO [15][16][17][18], injection-locked OEO [19][20][21][22], OEO with quality multiplier [23], and OEO with feedback loop [24] are some of the well-known configurations. Moreover, optical solutions are possible by adding components such as optical filters [25][26][27] and optical amplifiers [28][29] or by adjusting the optical link to achieve an optical gain [30]. These are already used to improve the stabilization of the OEO. Since an OEO consisting of such bulky components is very large, some methods to reduce the size of the oscillator device have already been reported. There are several solutions such as using a whispering-gallery-mode resonator (WGMR) [31][32][33][34], a ring resonator [35][36], or an electro-absorption modulated laser [37] that decrease the size of the OEO. In 2017, a fully integrated OEO was reported in the literature by J. Tang et al. [38][39]. In addition, a theoretical and experimental study of the characteristics of an injection-locked OEO was presented and published in several journals [40][41][42][43][44]. Recently, a W-band OEO was introduced by G.K.M. Hasanuzzaman et al. [45]. The OEO provided a phase noise characteristic of −101 dBc/Hz at a 10 kHz offset from the 94.5 GHz carrier. On the other hand, an opto-electronic parametric oscillator [46] was reported in 2020.

There are some more recent developments in the use of OEOs in various applications. One example of this is terahertz (THz) photonic signal generation using an OEO [47][48][49]. Another possible application of an OEO is to use it as a local oscillator (LO) in the central office of a 5G radio access network (RAN) [50][51][52]. The single-loop OEO can be combined with an optical fiber path selector to measure the free spectral range (FSR) and side-mode suppression ratio (SMSR) of the OEO for different lengths of the optical delay line [53]. There are other applications of OEOs such as an acoustic sensor [54], low-power radio frequency (RF) signal detection [55], phase-locked loops [56][57][58], parity time-symmetric OEO [59][60], silicon micro-ring-based OEO [61] and linear frequency-modulated waveform generation [62], etc.

Long-term stability and side modes (multimode operation) are the main challenges affecting the stabilization of an OEO. The OEO uses an optical fiber that is mainly affected by the temperature variations in the environment. This leads to fluctuations in the oscillation frequency over time, which is referred to as the frequency drift (in other words, long-term stability). On the other hand, electrical bandpass filters have bandwidth limitations in the micro- and millimeter wave ranges. Electric bandpass filters are used in the oscillator loop to destroy the side modes in the RF spectrum and determine the main mode of the oscillation. Due to the bandwidth limitation of the filter, the side modes are not completely filtered out, and they can therefore be seen in the RF spectrum. The ratio between the fundamental mode and the spurious side modes is called SMSR.

The short-term stability (i.e., phase noise) is mainly based on the length of the delay line of the OEO. The OEO can use a long delay line to achieve the lowest possible phase noise. However, using a long delay line boosts the power of the side modes because the FSR becomes lower, and the side modes are more difficult to filter out due to the bandwidth limitation of the electrical filter. For instance, the use of a 1-km fiber has an FSR of 200 kHz, while a

15 km fiber has an FSR of 13.4 kHz. The relationship between SMSR and phase noise performance of the OEO at different optical lengths is shown in Figure 2.

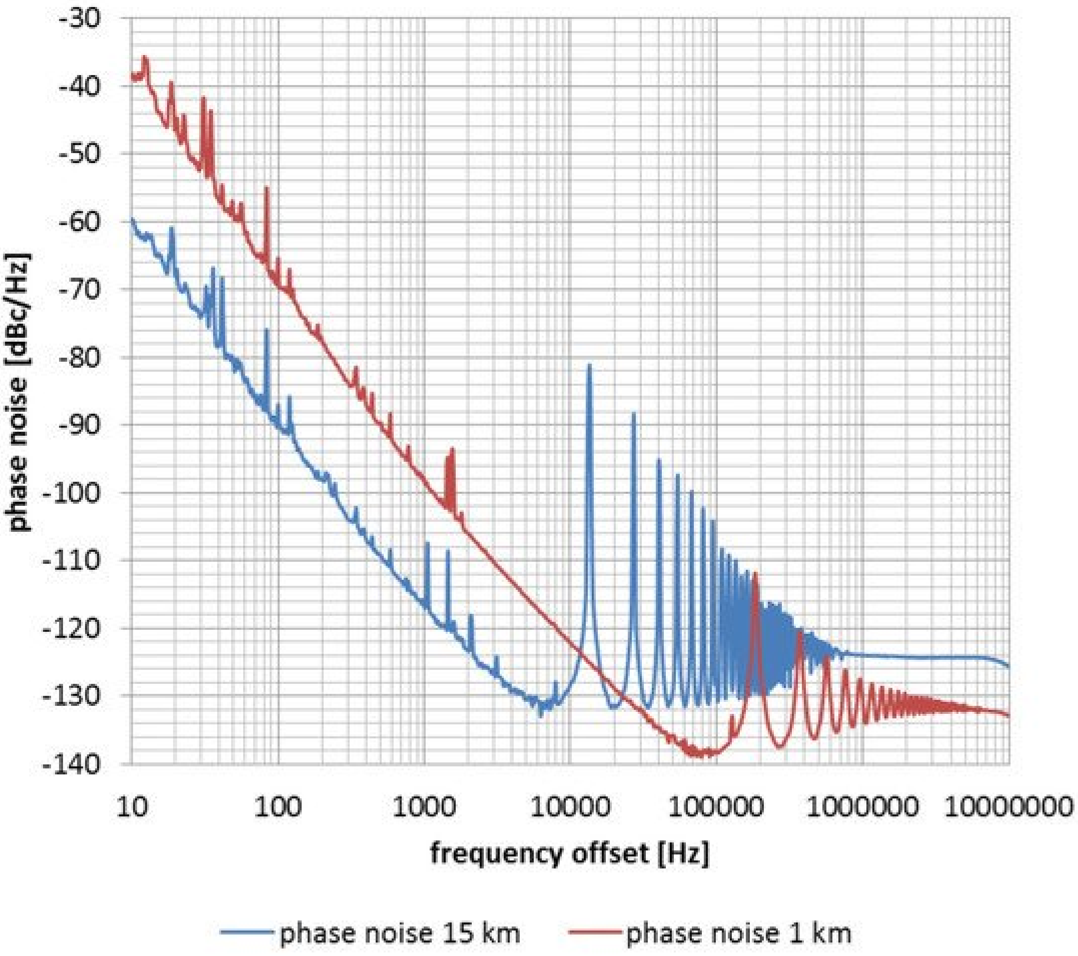

Figure 2. Comparison of phase noise and side-mode suppression ratio (SMSR) performance of OEO with 1 km and 15 km delay line length [1]. Reprinted with permission from ref. [1]. Copyright 2015 IEEE.

As can be seen from the experimental results in Figure 2, there is a tradeoff between the short-term stability and multimode operation of the OEO. The 1 km OEO has about a 30 dB improvement performance in the SMSR, but the 15 km OEO has a significant improvement in phase noise, which is about 20 dB at 1 kHz and 10 kHz offsets from the carrier.

2. Current Progress of the Common Topologies of the OEO

In this section, the paper focuses on recent advances in the development of OEOs and the main challenges that they face: multimode operation, as well as short-term and long-term stability. In the first subsection, the paper focuses on multimode operation and short-term stability, with long-term stability following this subsection.

2.1. Progress of the OEO toward Lower SMSR and Phase Noise

As mentioned earlier, one of the general challenges associated with OEO design is multimode operation. Since an electrical bandpass filter has bandwidth limitations, some optical solutions have been proposed. One of the most popular solutions is to form more than one optical delay line. These dual or multi-loop OEOs have seen widespread use for more than 20 years to eliminate multimode operation [63]. The typical configuration of a dual-loop OEO is shown in Figure 3. In this configuration, one loop is used as a long cavity, while the other behaves as a short cavity. This is achieved by using short and long fibers in different loops. One of the recent advances in the dual-loop OEO is the use of multicore fibers and the self-polarization-stabilization technique [64]. Conventionally, two or more single-mode fibers (SMFs) are used to form a dual- or multi-loop configuration. In this novel approach, the combination of cores in a multicore fiber is used to form a short and a long cavity [64]. With this novel approach, an SMSR of 61 dB was achieved for a microwave OEO oscillating at 7.8 GHz. Another recent approach is parity symmetry of the OEO with a dual-loop configuration [65]. The parity symmetry is achieved by using two optical carriers with different optical powers. Parity symmetry provides additional gain for the main mode. With the combination of parity symmetry and a dual loop, a 60.71 dB SMSR was achieved for a 10 GHz central frequency.

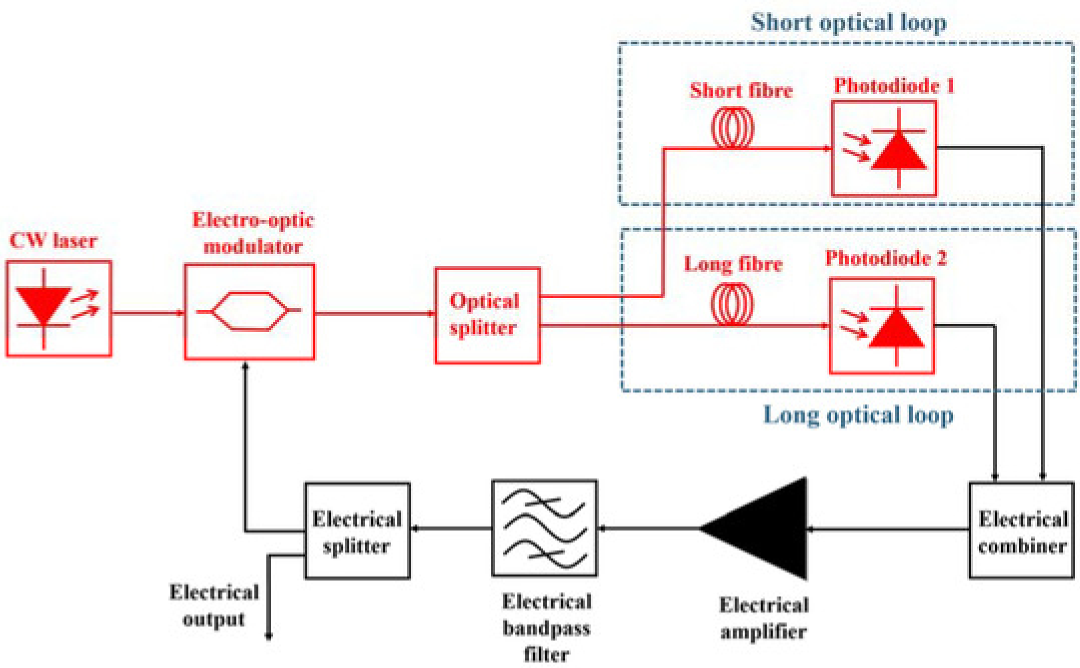

Figure 3. Typical dual-loop configuration of an OEO.

An injection-locked OEO is another configuration to improve the SMSR performance of the OEO. It was first proposed in 2005 [63][66]. The typical configuration of an injection-locked OEO is shown in Figure 4. In the typical configuration of the OEO, it consists of two oscillator blocks. One of them is classified as the master OEO and other as the slave OEO [63]. This approach is used to suppress the spurious side modes and at the same time maintain the quality factor (Q-factor) of the OEO [63]. The slave OEO is used to suppress the spurious side modes as it employs a short fiber, while the master OEO employs a long fiber to keep the high Q-factor. In reference [67], a tunable, dual-loop, injection-locked OEO was presented. The OEO was tunable from 11.1 GHz to 12.1 GHz, and the spurious side modes were suppressed below −115 dBc/Hz [67]. Another approach was to form a microwave frequency divider based on the injection-locked OEO [68]. In this implementation, the 10 GHz free-running OEO was injected with a 20 GHz microwave signal. A single-sideband (SSB) phase noise of −130 dBc/Hz at a 10 kHz offset was achieved. In Reference [69], an injection-locked OEO based on stimulated Brillouin scattering (SBS) is described. This approach provided a frequency tunability up to 40 GHz with an SMSR of 60 dB and an SSB noise of −116 dBc/Hz at a 10 Hz offset.

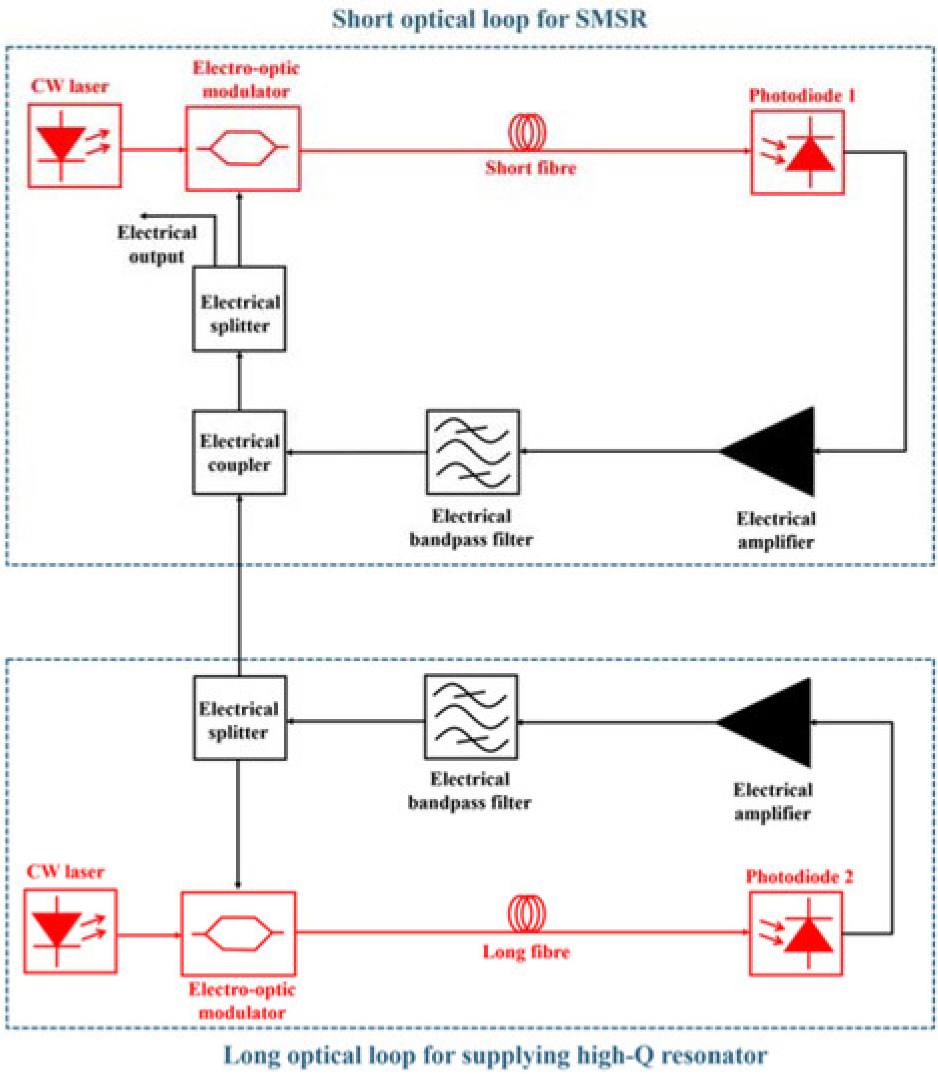

Figure 4. Typical injection-locked OEO.

The coupled OEO, introduced in 1997 [63][70], is another type of commonly used OEO configuration to improve SMSR. In this configuration, the OEO consists of an optical loop and an opto-electronic loop coupled via an electro-optic modulator [63]. The coupled OEO is used to improve the phase noise characteristics and the SMSR. The typical configuration of a coupled OEO is shown in Figure 5. An example of a recent development in the coupled OEO was the synthesis of a 90 GHz signal using a 30 GHz coupled OEO [71]. The 90 GHz signal was obtained by biasing the MZM to the third harmonic. An SSB phase noise of −104 dBc/Hz at a 1 kHz offset from the 90 GHz carrier was achieved in this configuration [71]. On the other hand, a novel, coupled OEO with an erbium-doped fiber (EDF) has been proposed [72]. The novel configuration allows a large spatial hole burning (SHB) using the unpumped EDF to improve the SMSR and the phase noise. An SMSR of more than 72.5 dB was achieved wherein the SSB phase noise was −123.6 dBc/Hz at a 10 kHz offset from the 10 GHz carrier signal.

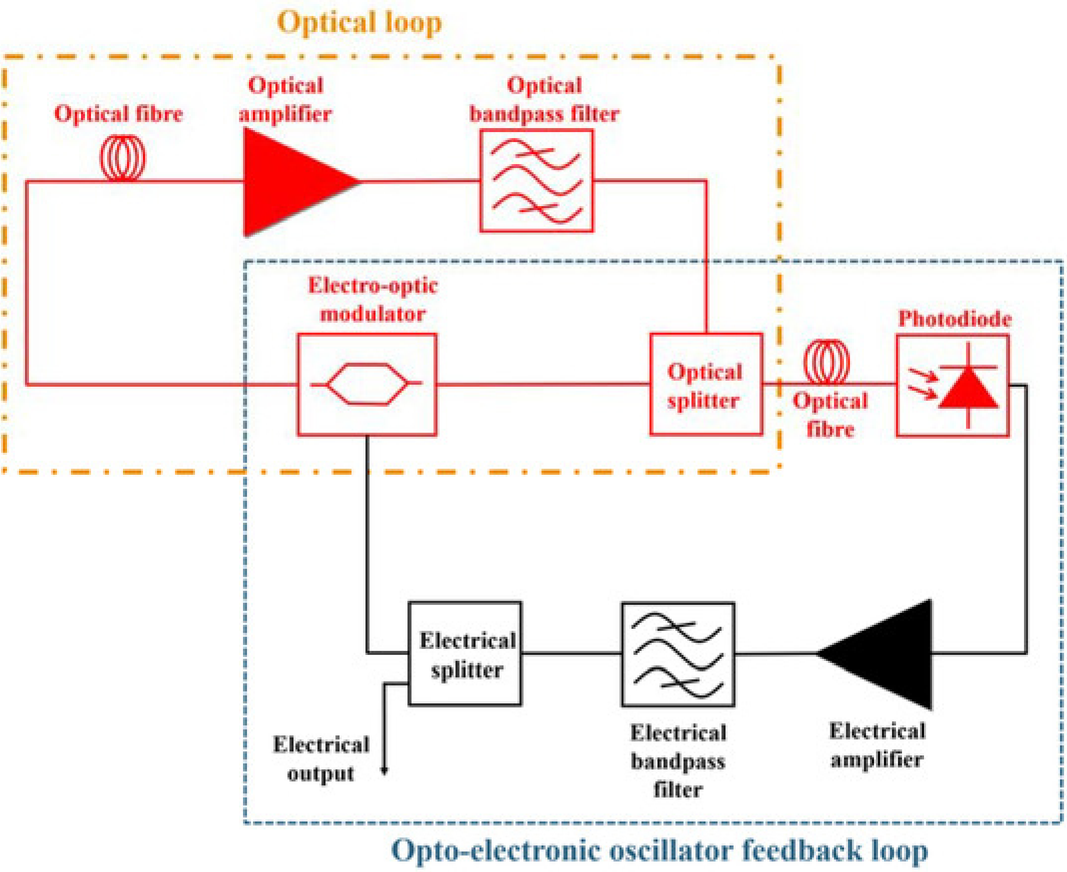

Figure 5. Typical configuration of a coupled OEO.

In addition to the typical solutions listed above, there are other novel solutions to improve the phase noise and/or the SMSR characteristics of the OEO. For a millimeter-wave OEO, a high-quality opto-electronic filter was proposed, e.g., a Q-factor of 30,000 at a central frequency of 29.99 GHz [73]. This resulted in an 83 dB SMSR and a −113 dBc/Hz SSB phase noise at a 10 kHz offset. A cascaded microwave filter was presented in [49]. In this configuration, the cascaded filter configuration was implemented with a single passband filter having an opto-electronic filter. With this approach, an SMSR of 125 dB and an SSB phase noise of −103 dBc/Hz for a 10 kHz offset at the 17.33 GHz carrier were achieved. The linewidth of the laser can affect the phase-noise performance of the OEO. A narrowband microcavity laser with a physical side length of 16 μm is used for the microwave signal generation in the loop of the OEO [74]. An SSB phase noise of −116 dBc/Hz was achieved for a 10 kHz offset from the carrier microwave signal. The microwave signal can be tuned between 1.85 GHz and 10.24 GHz thanks to a tunable optical bandpass filter.

2.2. Progress of the OEO toward Better Long-Term Stability

Long-term stability is another important characteristic of the OEO. The electrical bandpass filter and the optical fiber are major components of the OEO that are temperature-dependent [75]. For the frequency drift of a nontemperature-stabilized OEO operating at a 10 GHz central frequency, 8 ppm/K was measured [75]. One of the useful approaches is the temperature stabilization of the optical fiber and the electrical bandpass filter of the OEO loop [75]. With this solution, 0.1 ppm/K was achieved. In 2016, Luka Bogataj et al. brought another approach, i.e., the OEO with a feedback control loop [24][76]. The configuration of the feedback control loop is shown in Figure 6.

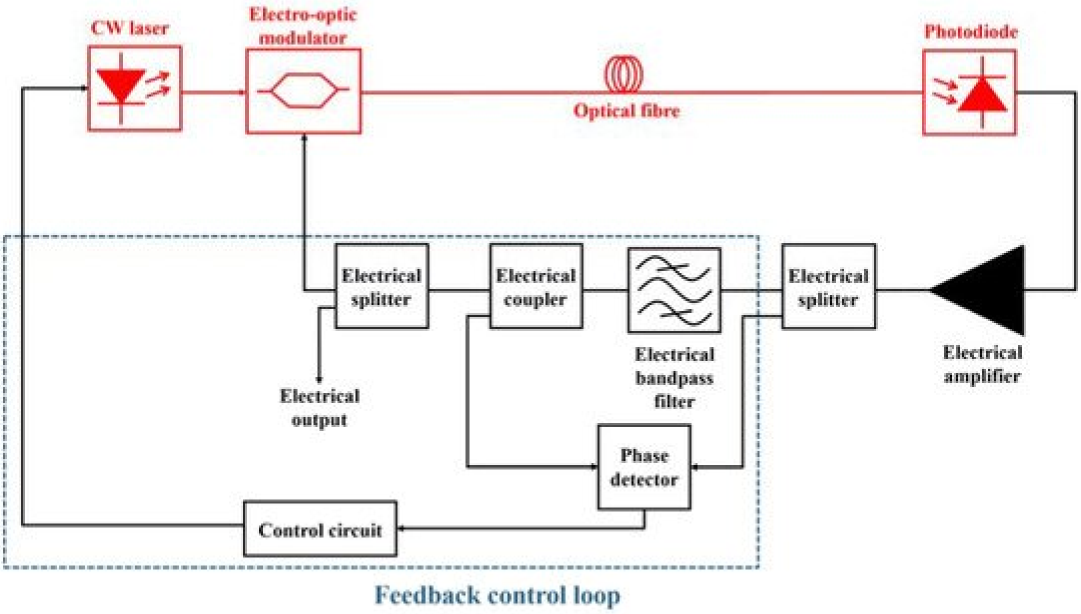

Figure 6. OEO with a feedback-control loop.

In the feedback control loop, the frequency discriminator controls the temperature of the laser by measuring the refractive index of the optical fiber. A proportional–integral (PI) controller is used to control the temperature of the laser. Using the feedback control loop, a frequency drift of 0.05 ppm/K was achieved for a single-loop OEO operating at 3 GHz. In 2017, the optical delay stabilization system (ODSS) was introduced [77] for active fiber delay stabilization at a different wavelength than used in the oscillator loop. The outstanding result of a 0.02 ppm/K frequency drift was achieved for a 3 GHz OEO. However, the frequency of the oscillator can be increased, but this does not affect the stability result because the stabilization is performed at an independent wavelength.

Phase-locked loops (PLLs) are alternative solutions that are widely used in practice to improve the long-term stability of the OEO signal. In this case, the OEO signal is locked by the PLL signal [78]. The typical configuration of an OEO with a PLL is shown in Figure 7.

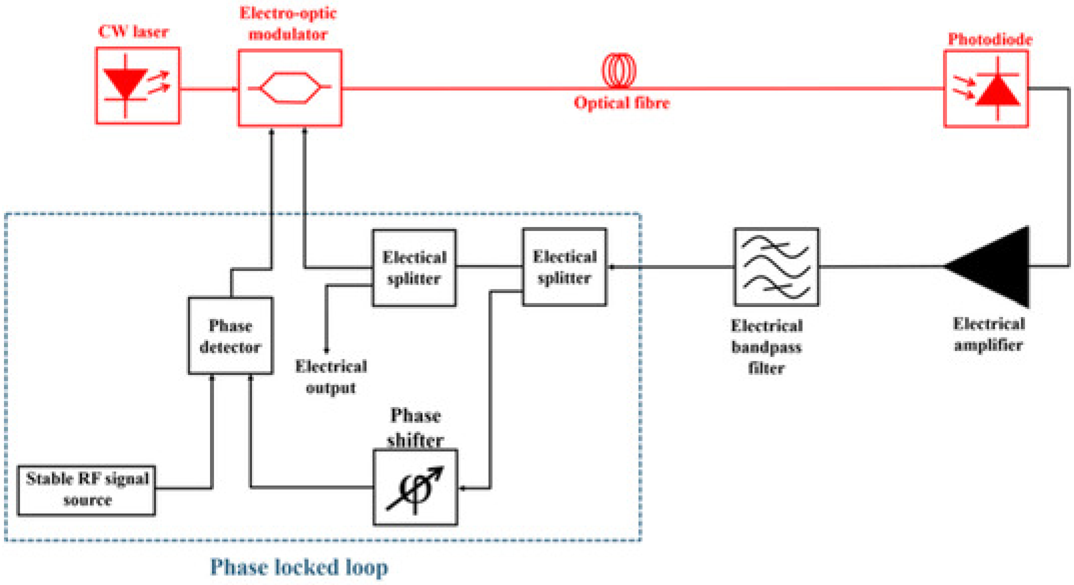

Figure 7. Typical configuration of an OEO with a PLL configuration.

For an OEO with a PLL configuration, a stable reference signal is required to improve the long-term stability. Wen-Hung Tseng proposed another approach to improving the long-term stability that involves a fiber-delay monitoring mechanism [79]. This mechanism monitors the fiber delay using an injected probe signal. A thermal drift of 10^{-7} s was achieved after 4000 seconds with the monitoring mechanism.

2.3. General Overview

In this section of the paper, we would like to compare the performance of different configurations of the OEO in multimode operation: short-term stability (i.e., phase noise) and long-term stability. In the first table, different configurations of the OEO are described by comparing the SMSR and the phase noise.

For Table 1, OEOs with the same or similar frequency were selected (except for the OEO with a high quality opto-electronic filter) to allow a more accurate and scientific comparison of the phase noise in different solutions. However, in theory, the OEO has a stable phase-noise characteristic that is independent of the operating frequency [1], so higher frequencies can be used for the comparison. In the SMSR comparison, the optical delay line length and the bandwidth of the electrical and/or optical filter are more important for the comparison. When considering the phase noise, the injection-locked OEO achieves the best performance among the other solutions. On the other hand, the cascaded micro-wave photonic filter solution achieved a better result in terms of the SMSR.

Table 1. Comparison of the SMSR and the phase noise of the current results for various advanced configurations of the OEO.

Configuration	Optical Delay Line Length	Central Frequency	SMSR	Phase Noise (@10 kHz offset from the carrier)
Dual-loop OEO [64]	7-core fiber	From 3.5 GHz to	61	−100 dBc/Hz

Configuration	Optical Delay Line Length	Central Frequency	SMSR	Phase Noise (@10 kHz offset from the carrier)
	(105 m)	17.1 GHz	dB	
Injection-locked OEO [68]	Single-mode fibers (1 km and 0.7 km)	10 GHz	N/A	−130 dBc/Hz
Coupled OEO [72]	Erbium-doped fiber (4 m)	10 GHz	72.5 dB	−123.6 dBc/Hz
OEO with high-quality opto-electronic filter [73]	Dispersion-shifted fiber (3 km)	29.99 GHz	83 dB	−113 dBc/Hz
Cascading microwave photonic filter [49]	Single-mode fibers (2 km and 0.2 km)	17.33 GHz	125 dB	−103 dBc/Hz
Narrowband microwave laser with dual-loop OEO [74]	Single-mode fibers (2.5 km and 3 km)	From 1.85 GHz to 10.24 GHz	55 dB	−116 dBc/Hz

n stability and phase noise.

Table 2. Comparison of the different techniques to achieve long-term stability in the OEO.

Configuration	Optical Delay Line Length	Central Frequency	Long-term Stability	Phase Noise (@10 kHz offset from the carrier)
Temperature stabilization [75]	N/A	10 GHz	0.1 ppm/K	−143 dBc/Hz
OEO with feedback-control loop [76]	15 km	3 GHz	0.05 ppm/K	< −130 dBc/Hz
Optical delay stabilization system [77]	3 km	3 GHz	0.02 ppm/K	−123 dBc/Hz
OEO with PLL [78]	500 m (Dispersion deduced fiber)	3 GHz	6.98×10^{-14} (average time of 1000 s)	< −100 dBc/Hz

The optical delay line system showed good performance in terms of long-term and short-term stability. The phase-noise performance could be improved by using a longer optical fiber. An OEO with a PLL does not have good phase noise performance because a short delay line is used. However, a classic solution such as temperature stabilization has good phase noise performance and short-term stability.

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