Ultra-high-Q Optoelectronic Oscillator based on Bilaterally Coupled Loops

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***Abstract*—An optoelectronic oscillator (OEO) based on bilateral coupling between two individual optoelectronic loops is demonstrated. The resulting OEO has two modes of operation, in which the individual loops either oscillate or act as IIR filters. A Q-factor greater than 10^{10} at 5.8 GHz is observed.**

***Keywords*—optoelectronic oscillator;coupled oscillator; microwave photonics; microwave generation;Q-factor**

I. INTRODUCTION

One of the key areas in microwave photonics is the use of photonic techniques to generate high quality microwave signals for applications such as radar and communications [1]. In this respect the optoelectronic oscillator (OEO) has been widely studied for several years because of the capability of producing very low phase noise signals, both as an RF and as a modulated optical output [2]. Apart from phase noise, other important figures of merit include stability and the quality factor. Indeed a high Q-factor is required to reduce phase noise, which in single-loop oscillators implies long fiber loops; this in turn leads to several side modes appearing close to the peak oscillation on account of the reduced free spectral range (FSR). This has motivated the development of dual-loop [3] and even multi-loop [4] topologies in which a short loop ensures side mode suppression while the long loop preserves the high Q. However, the side modes are not completely suppressed and the overall Q-factor is averaged amongst the short and long fiber loops [5]. Alternative approaches based on injection locking have therefore been investigated, in which a long-loop OEO acts as a master oscillator providing high Q and the short-loop OEO then filters out the dominant mode of oscillation [6,7]. These are essentially unilaterally coupled oscillator pairs similar to systems of coupled conventional microwave oscillators [8], although bilateral coupling has also been investigated [9]. When the microwave bandpass filter is removed, two or more coupled optoelectronic oscillators can demonstrate a rich variety of dynamics, including chaos [10].

In this work, we demonstrate a new approach to bilaterally coupled OEOs resulting in an ultra-high-Q in excess of 10^{10}. Our topology differs from other coupled OEOs in that it is formed from coupled optoelectronic loops driven from a single laser source, can function without a microwave bandpass filter and the coupling is implemented optically in one direction and with electro-optic conversion (via a Mach-Zehnder modulator – MZM-0) in the reverse direction, as shown conceptually in Fig.1. We define an optoelectronic loop (OEL) as being equivalent to a single-loop OEO without a laser source, i.e. it comprises in its most basic form a MZM the output of which, after passing through a length of fiber, is photo-detected and then connected to the MZM's drive electrode.

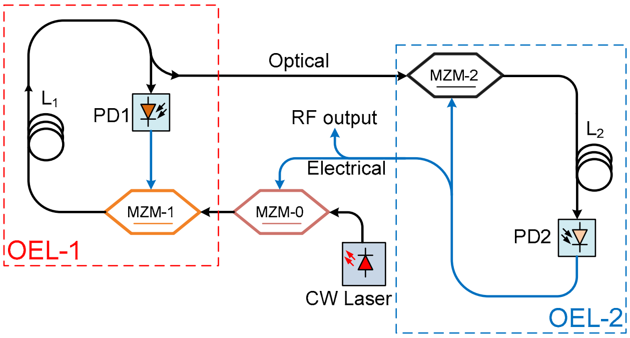

Fig.1: Proposed concept of an OEO formed from bilaterally coupled OELs. Microwave and optical amplifiers, couplers and filters are not shown for simplicity.

A unique feature of this implementation is that it can operate in two basic modes. In the first, OEL-1 and OEL-2 both have loop gains greater than one and the system in Fig.1 then acts as a pair of coupled oscillators. Furthermore, the overall system will still oscillate even when the individual OELs have loop gains below unity. In this second mode of operation OEL-1 and OEL-2 act as cascaded microwave photonic IIR filters which then provide an infinite number of taps, leading to high Q-factors. Here we present measured results for both modes of operation.

II. EXPERIMENTAL SETUP

The bilaterally coupled loop OEO (BCL-OEO) is shown in Fig. 2. A quadrature- biased Mach-Zehnder modulator (MZM-0) is fed by a distributed feedback laser (DFB) of optical power 11dBm at a wavelength of 1550.12nm and -140dBc/Hz

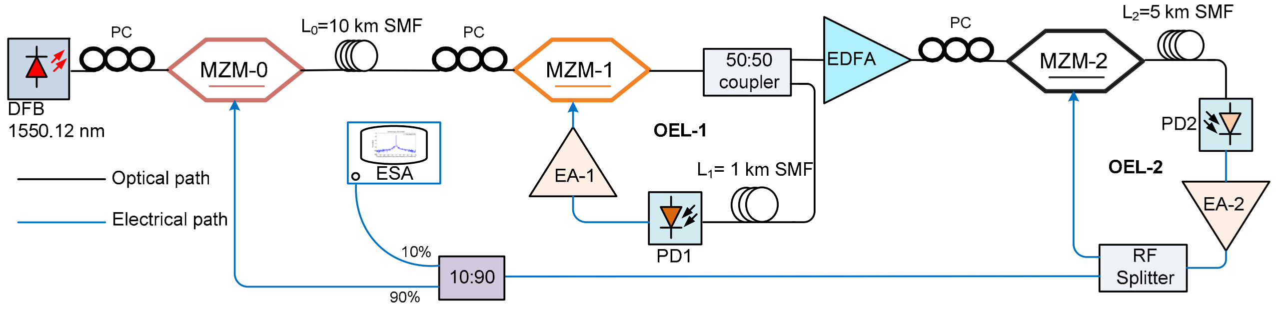

Fig.2. Schematic diagram of the experimental BCL-OEO system. PC: Polarization Controller, SMF: Single-Mode Fiber, EDFA: Erbium-Doped Fiber Amplifier, ESA: Electrical Spectrum Analyzer. (Note: “EA” is realized with a cascade of two microwave amplifiers.)

relative intensity noise (RIN). The output from MZM-0 is delayed by a fiber of length L_0 prior to entering the first optoelectronic loop (OEL-1), which consists of a quadrature-biased MZM-1, a fiber length L_1, a high-speed photodiode (PD1) and a low-noise amplifier (EA-1) which feeds the RF port of MZM-1. A subsequent 3-dB coupler splits the output of MZM-1 into two paths. The lower path is delayed by a single mode fiber (SMF) of 1 km length (L_1) and detected by a high speed photodiode. A low noise amplifier (EA-1) then amplifies the generated microwave signal before being fed back to MZM-1. The upper path of the modulated light-wave is then injected into another quadrature biased modulator (MZM-2) where a 5 km SMF (L_2) delays its optical output which is finally converted to the electrical domain via photodiode PD2. After low noise amplification (EA-2), an RF splitter equally divides the microwave signal with the first output being fed back to the RF port of MZM-2 (thus forming OEL-2) and the other output being fed back to MZM-0, thereby composing the overall OEO structure and final microwave oscillation. The RF splitter distributes the gain to the two branches, minimizing the number of electronic amplifiers required to sustain an oscillation. Operating an OEO with fewer amplifiers reduces the power consumption and more significantly the system’s flicker noise, resulting in improved phase noise performance and spectral purity.

An EDFA is used to compensate the insertion losses from MZM-1 and the 3 dB coupler. It also provides sufficient gain to OEL-2 and the overall loop back to MZM-0 in order to sustain oscillations. The EDFA is placed outside the OEL-1 and OEL-2 loops so that recirculating waves are free from additional delays, maintaining the free spectral range, which is determined from fibers L_1 = 1 km and L_2 = 5 km (the choice of fiber lengths was constrained by the available fiber spools in our laboratory). All three MZMs are nominally identical with V_π = 5.1V and are biased at the positive slope quadrature point ($3V_\pi/2$).

III. RESULTS AND DISCUSSION

The bilaterally coupled loop OEO has been investigated for both modes of operation as referred to in §I, viz. for (i) OEL-1 and OEL-2 both having loops gains greater than unity and for (ii) OEL-1 and OEL-2 both having loops gains less than unity.

Measured electrical spectra at four different spans are shown for the first case in Figs. 3(a)-3(d). Initially a fiber spool was not inserted between MZM-0 and MZM-1 (i.e. L_0 was set to zero). The oscillating modes of OEL-1 are injected optically into OEL-2, thus enhancing the Q-factor while maintaining the FSR of OEL-1. The FSR of OEL-1 and OEL-2 is 214 kHz and 40 kHz respectively as shown in Fig. 3(b). A fiber of length L_0=10 km was then inserted; not only did the FSR of the entire system not decrease, but the side modes appearing every 200 kHz were suppressed by 10 dB thus achieving an enhanced purity OEO.

The center frequency of the high purity oscillating signal is 5.8 GHz. As seen in the spectra of Figs 3(c) and 3(d) where smaller spans and resolution bandwidths (RBW) are selected (down to 3 Hz RBW and 500 Hz span), the generated microwave signal has a 3-dB bandwidth that lies in the sub-Hz region corresponding to a Q-factor in excess of 10^{10}. The multimode spurs are significantly suppressed, leading to a side mode suppression ratio (SMSR) of 50 dB to 65 dB. The frequency drift of this system is approximately 70 Hz/s. The noise floor of the OEO, measured at 3Hz RBW and 500 Hz SPAN, is -70 dBm and the spectrum analyzer has a displayed average noise floor (DANL) of -110dBc at 100 Hz offset.

Fig. 4 displays the single side-band (SSB) phase noise measurement of the generated microwave signal captured by the electrical spectrum analyzer (Agilent E4407B) using the phase noise personality Option 226. The phase noise is measured at -83 dBc/Hz and -104 dBc/Hz at 10 kHz and 1 MHz offset from the carrier respectively. After connecting the L_0 = 10 km SMF in the system, the phase noise at lower frequency offsets is improved (i.e. decreased) by 5 dBc and, where side-modes appear, the phase noise is further decreased by 7 dBc. The OEO's phase noise measurement is mixed with the phase noise and noise figure (DANL) of the spectrum analyzer. This problem arises for low phase noise sources measured with the direct method technique [11]. A way to distinguish the measured signal from the analyzer's noise is to apply the cancellation method. The magenta line in Fig. 4 shows the phase noise performance of the system after the noise of the spectrum analyzer is removed, leading to a measured average phase noise of -117 dBc/Hz at 10 kHz offset and -129 dBc/Hz at 1 MHz offset.

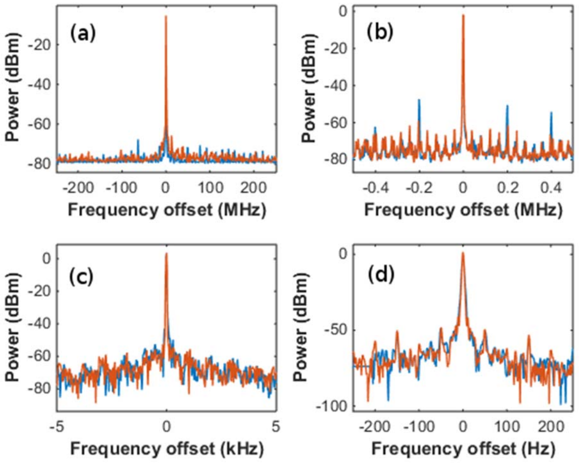

Fig.3. Electrical spectra of the generated 5.8 GHz oscillation with L_0=10 km attached (red) and detached (blue) at: (a) RBW: 10 kHz, SPAN: 500 MHz, (b) RBW: 1 kHz, SPAN: 1 MHz, (c) RBW: 30 Hz, SPAN: 10 kHz and (d) RBW: 3 Hz, SPAN: 500 Hz.

The second mode of operation of the bilaterally coupled loop OEO was also investigated, in which OEL-1and OEL-2 are reconfigured as microwave photonic IIR filters by reducing their loop gains to less than unity. This is implemented by inserting two variable optical attenuators (VOAs) before each photodiode and also applying a microwave amplifier at the RF input port of MZM-0 to maintain the loop gain of the overall OEO. The feedback loop IIR filters operate efficiently at loop gains just below unity where intermodulation impairments are prevented. The rejection ratio and frequency selectivity may also be increased.

According to Fig. 5, the oscillation peak extinction ratio from the noise floor slightly increases due to the addition of an extra amplifier. The achieved oscillation peak is very sharp as shown in Figs 5(c) and 5(d), exhibiting a sub-Hz 3-dB bandwidth and a Q-factor in excess of 10^{10}. The SMSR begins to increase from 40 dB reaching 60 dB at an offset of 365 kHz. This figure can be further increased by replacing the VOAs with microwave attenuators immediately after photodetection because the additional microwave amplifier, inserted at the RF input of MZM-0, will no longer be needed. This in turn will lead to a lower noise floor (and reduced phase noise) in addition to minimized intermodulation products through decreasing the electrical gain and increasing the optical gain.

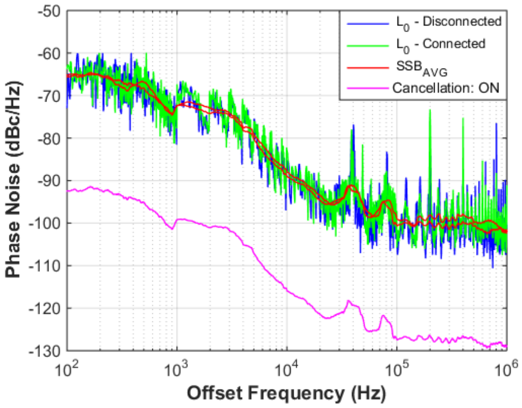

Fig.4. Single side-band (SSB) phase noise measurement of the generated microwave signal at 5.8 GHz for the case in which OEL-1 and OEL-2 both have loop gain magnitudes greater than unity and hence the overall system acts as a pair of coupled optoelectronic oscillators.

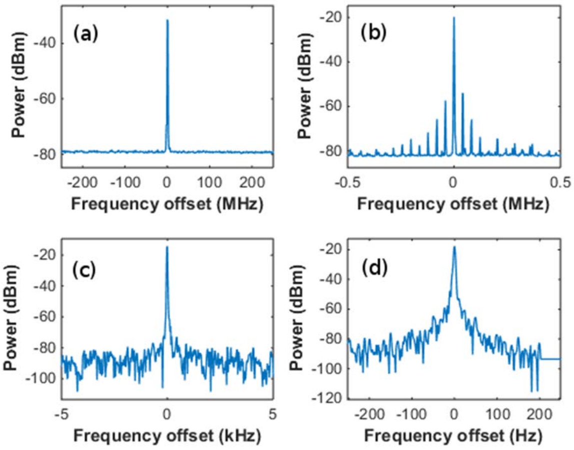

Fig.5. Electrical spectra of the generated 5.8 GHz oscillation for the case in which OEL-1 and OEL-2 both have loop gain magnitudes less than unity and with L_0=10 km inserted in the system at: (a) RBW: 10 kHz, SPAN: 500 MHz, (b) RBW: 1 kHz, SPAN: 1 MHz, (c) RBW: 30 Hz, SPAN: 10 kHz and (d) RBW: 3 Hz, SPAN: 500 Hz.

The single side-band (SSB) phase noise measurement of the microwave signal is shown in Fig. 6. The phase noise is measured as -87 dBc/Hz and -93 dBc/Hz at 10 kHz and 1 MHz offsets from the carrier respectively. After applying the cancellation method, the phase noise was measured at -114 dBc/Hz and -119 dBc/Hz at 10 kHz and 1 MHz offsets. The phase noise is very low because the photonic filter is coherence-free, i.e. free from any optical or electrical interference and it is not limited by any phase-induced intensity noise.

In both modes of operation, the oscillation frequency of the bilaterally coupled loop optoelectronic oscillator can be tuned by changing the fiber lengths of OEL-1 and OEL-2, the overall gain of the system or by negatively biasing the MZMs. For the first scenario (loop gain greater than unity) the fundamental frequencies are doubled, while at negative bias and for the case in which OEL-1 and OEL-2 operate as a microwave photonic IIR filter cascade, the passband and stopband of the filter interchange.

More specifically, for the first case in which OEL-1 and OEL-2 both have loop gains in excess of unity, the tuning range is determined from the loop with the shorter length (OEL-1) while the tuning resolution is obtained from the longer loop (OEL-2). In contrast, for the second case in which OEL-1 and OEL-2 operate as an IIR filter cascade the frequency tuning of the overall OEO is defined by the minimum least common multiple of the two combined FSRs.

The bilaterally coupled OEO has also been investigated for the situation in which a narrowband microwave bandpass filter with a 10 GHz center frequency was inserted immediately before the microwave 10:90 coupler, and it was possible to achieve oscillation at 10 GHz when OEL-1 and OEL-2 had loop gains below unity.

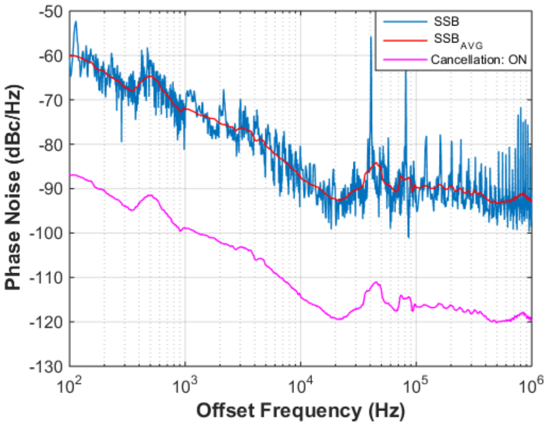

Fig.6. Single side-band (SSB) phase noise measurement of the generated 5.8 GHz signal for the case in which OEL-1 and OEL-2 both have loop gain magnitudes less than unity and hence acts as a pair of cascaded microwave photonic IIR filters.

IV. CONCLUSIONS

A bilaterally coupled loop OEO has been experimentally implemented in which two individual optoelectronic loops (OEL-1 and OEL-2) are combined using optical coupling in one direction (via an intermediate EDFA) and through electro-optic conversion using a MZM in the other direction. The overall OEO can be configured to oscillate under two modes of operation. In the first, both OEL-1 and OEL-2 have individual loop gain magnitudes in excess of unity, and the whole system acts in a similar manner to other systems of coupled microwave oscillators [8], exhibiting ultra-high Q oscillations (in excess of 10^{10}). However, this is at the expense of potential system instability due to the loop gains being bigger than unity. In the second mode of operation, OEL-1 and OEL-2 are no longer able to oscillate due to having loop gains less than unity, and instead act as a pair of microwave photonic IIR filters in cascade. In this case the overall system still oscillates in an analogous manner to a conventional single-loop OEO, and while the phase noise is not as good for the first mode, a Q-factor in excess of 10^{10} is still measured and any potential loop instabilities are avoided.

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