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High-Q wavelength division multiplexed optoelectronic oscillator based on a cascaded multi-loop topology

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ABSTRACT

A WDM optoelectronic oscillator (OEO) based on a cascaded optical multi-loop configuration and multiple photodiodes is proposed and demonstrated experimentally. By employing up to three lasers widely separated in wavelength along with two cascaded multi-loop fiber sections and two photodiodes, we demonstrate OEO topologies that scale up to six effective loops revealing an ultra-high quality factor in excess of 10^{10} and a phase noise performance down to −119 dBc/Hz at 10 kHz offset

1. Introduction

Since it was first reported in 1995, the optoelectronic oscillator has attracted much interest owing to the high quality and low phase noise microwave signals that can be generated [1]. The simplest topology consists of a single closed hybrid loop containing an optical path (typically several km of single mode fiber which acts as an energy storage element) and a microwave path (typically containing an amplifier, bandpass filter, and RF output coupler). The trade-off between high Q-factor and the presence of side modes for single-loop OEOs with long fiber lengths is well documented. This has resulted in a plethora of techniques aimed at simultaneously suppressing the side modes whilst maintaining a high Q-factor [2,3], with optoelectronic oscillators having been demonstrated up to mm-wave frequencies [4].

A popular method for side mode suppression is based on the use of multi-loop configurations. This approach was first developed by Yao and Maleki [5], in which the optical part of the loop was split into two parallel paths – a long loop in order to establish a high Q-factor (but small FSR) and a short loop with a large FSR – which are then recombined to produce a Vernier effect. In [5], the loops were recombined coherently (after individual photodetection) via a microwave coupler. A similar strategy has been adopted in other work to show how more than two paths may be employed to optimize the phase noise reduction [6] or how multicore fibers may replace multiple fiber spools [7]. In [8] injection locking was used in conjunction with a dual loop topology to suppress the side modes. Instead of using a classical dual loop configuration, a single loop configuration with a quality multiplier (an electronic feedback circuit designed to reduce the bandwidth of the microwave bandpass filter) has also been used filter to increase the side mode suppression ration (SMSR) [9]. In all of these approaches a single optical source is used.

It is also possible to recombine multiple loops optically through the use of multiple wavelengths, although interference effects may arise when the beams are superimposed. Other techniques for multi-loop topologies comprise multiplexing configurations where fiber Bragg grating (FBG) reflectors are used to separate the different wavelengths into different paths prior to detection in a single photodiode [10]. However, these configurations suffer from optical carrier dispersion and coherence problems due to the recombination of the optical carrier with its reflection. As a consequence, the quality factor and phase noise performance of the OEO at low offsets is degraded. In [11] a dual-wavelength dual-loop topology free from interference effects was demonstrated in conjunction with one photodiode, exhibiting a μHz class Q-factor and a phase noise of −125 dBc/Hz at a 10 kHz offset. This topology was further enhanced by the same authors through the implementation of feedback control for highly stable operation [12].

In this study, we aim to extend the above techniques by proposing and demonstrating a new approach in which the multi-loop topology of [5] is combined with the wavelength division multiplexing employed in [11]. Our topology is in essence based on a cascade of two finite impulse response (FIR) multiple source microwave photonic filters [13], in which interference beating effects are avoided because the employed wavelengths are coarsely spaced. Considering the microwave photonic filter portion of the resulting OEO, the number of taps is given by the product of the number of lasers and photodiodes used; alternatively, this product is seen to represent the number of effective loops in the overall OEO. The effect on phase noise reduction due to scaling in the number of laser sources and/or photodiodes is examined experimentally. With three lasers and two photodiodes available, we were able to implement up to six effective loops; the implemented OEO

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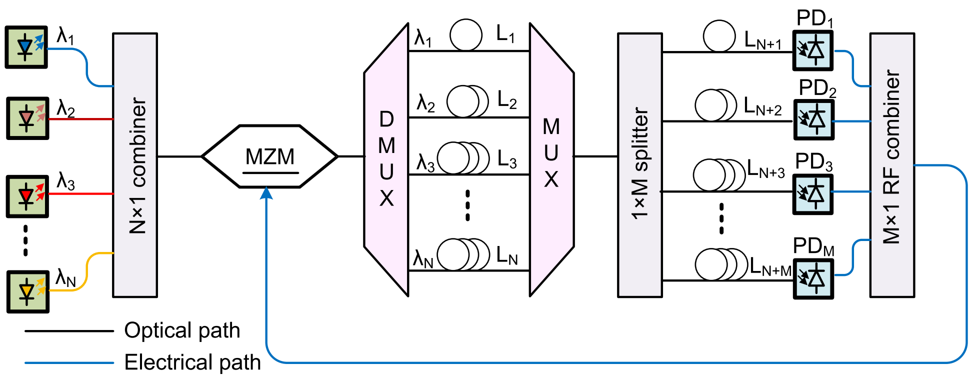

Fig. 1. Conceptual diagram of WDM multi-loop OEO. MZM:Mach-Zehnder modulator, DMUX:Demultiplexer, MUX:Multiplexer, PD:photodiode.

exhibits an ultra-high quality factor in excess of 10^{10} and a phase noise performance in the range −115 dBc/Hz to −125 dBc/Hz at 10 kHz offset, with this improving for an increased number of effective loops.

2. Proposed architecture and concept

The proposed OEO concept is depicted in Fig. 1. An array of N widely and equally spaced optical carriers is combined and fed to a Mach-Zehnder Modulator (MZM). A subsequent demultiplexer (DMUX) separates the modulated optical carriers, which then traverse optical cavities implemented as single mode fibers (SMF) of lengths L_1through to L_N. The individual fibers are then recombined using a multiplexer (MUX). Previously reported WDM multiloop OEOs [10–12] are implemented using a single photodiode (PD), resulting in an effective number of loops equal to the number of optical cavities (or sources), in this instance N_S. In this scheme, we consider a second successive optical multiloop section composed of N_P different delays with each optical section fed to a separate PD. Between the RF input to the MZM and the RF combiner output, the configuration can be regarded as a dual section FIR microwave photonic filter with a higher number of taps (N_SN_P) compared to using either the WDM section or multiloop section in isolation. In the context of microwave photonic FIR filters, increasing the number of taps will increase the filter's Q [14]. The WDM multiloop OEO structure is completed by connecting the RF combiner to the RF input of the MZM. Under steady-state sinusoidal oscillation conditions, the overall structure will then be a recursive system in which the Q-factor will be further enhanced due to the loop gain [14] and the presence of N_SN_P different loops, thereby leading to an oscillation of a higher Q-factor and potentially better phase noise performance.

3. Experimental results

The experimental setup is depicted in Fig. 2 for a system supporting up to three wavelengths (N_S≤3) and two photodiodes (N_P≤2). Systems with an effective number of loops corresponding to two (N_P=1, N_S=2), three (N_P=1, N_S=3), four (N_P=2, N_S=2) and six (N_P=2, N_S=3) were investigated. The first experiment considered an OEO with a single photodiode (N_P=1, i.e. scenario (A) in Fig. 2) and two independent (N_S=2) continuous wave optical sources of wavelengths λ_1=1550.12 nm and λ_2=1529.14 nm of relative intensity noise (RIN) −140 dB/Hz combined with an optical coupler. The wavelength separation was sufficiently large so as to avoid beating effects in the photodiode. The two light waves fed a quadrature biased MZM with subsequent amplification via an erbium doped amplifier (EDFA) to compensate the overall optical losses. A DMUX separated the amplified light wave into two optical carriers for subsequent transmission through two different paths of fiber lengths L_1=1 km and L_2=5 km. These specific fiber lengths were chosen to suppress the intermediate side modes, as shown in Fig. 3(a) and (b). The two optical carriers were recombined after transmission though L_1 and L_2 via a MUX and were detected by a high speed photodiode (PD) before closing the electrical loop by connecting the PD output to the RF input of the MZM.A broadband microwave amplifier (EA) was used at the output of the PD to provide the necessary gain for sustaining a steady-state oscillation.

Fig. 3(a) shows the measured microwave oscillation spectra of the two individual loops with the short loop (blue trace) delivering a large free spectral range (FSR) and the long loop (red trace) a narrower 3 dB bandwidth. When both loops are connected in the system, each individual loop can have a gain lower than unity but the overall loop gain of the dual-wavelength single-photodiode OEO must be greater than unity. Fig. 3(b) shows the resultant microwave oscillation centered at 15 GHz obtaining its FSR from the short (1 km) loop and its 3 dB bandwidth from the long (5 km) loop. A side-mode suppres-

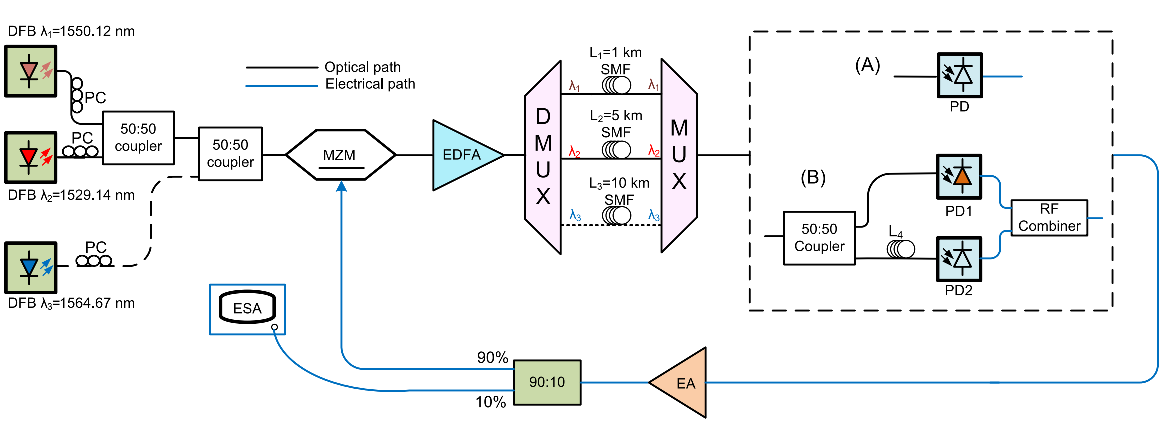

Fig. 2. Schematic diagram of the experimental WDM multi loop OEO based on either two or three laser sources and one photodiode (A) or two photodiodes (B). PC:Polarization Controller, DMUX:Demultiplexer, MUX:Multiplexer, SMF:Single Mode Fiber, ESA:Electrical Spectrum Analyzer.