A preliminary study on side mode suppression in optoelectronic oscillators using a two-mode optical fiber in the feedback loop

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Abstract

We discuss the use of a two-mode step-index fiber in the optical path of an optoelectronic oscillators as an alternative to a dual loop. The idea is to exploit the different group velocities of two LP fiber modes instead of using two single-mode fibers with different lengths. The basic theory of dual-loop oscillators can therefore be reused in this context. Nevertheless, due to a generally small group delay between two fiber modes, compared to the loop delay, the proposed idea needs a preliminary analysis.

1 Introduction

An optoelectronic oscillator (OEO) is able to produce high spectral purity carriers in the millimeter-wave range [1–3]. The limit in the spectral purity is mainly due to the relative intensity noise of the laser, the excess noise added by the optical amplifier, and shot noise related to the photodetection. As demonstrated in [2], the phase noise can be reduced by increasing the loop-delay time. In addition, using two feedback loops with different delay times, i.e. two single-mode fibers with different lengths, allows to suppress unwanted resonant frequencies, otherwise difficult to suppress with standard radio-frequency band-pass filters.

The idea proposed in this work is to replace the dual loop with a single one, maintaining the same working principle; instead of using two different fiber lengths, one fiber and two modes with different group velocities are considered. Multiple modes can be simultaneously and easily excited by means of radial offset launching [4, 5] or mechanically induced long-period gratings [5, 6], for example. Besides the use of one fiber only in the feedback loop, the main advantage of the proposed configuration, compared dual-loop OEOs, is the absence of the optical splitter and the optical or electrical combiner. The reader can refer to [7, 8] for a comparison with the proposed schematic, depicted in Fig. 1. A laser source is modulated by a Mach-Zehnder modulator (MZM) and amplified by an erbium-doped fiber amplifier (EDFA). The output fiber of the EDFA is spliced to a two-mode fiber (TMF) using the offset splicing technique, in order to equally excite both propagating modes. Using the same technique, the other end of the TMF is then spliced to the single-mode input fiber of the photodetector (PD), whose radio-frequency (RF) output is then amplified and

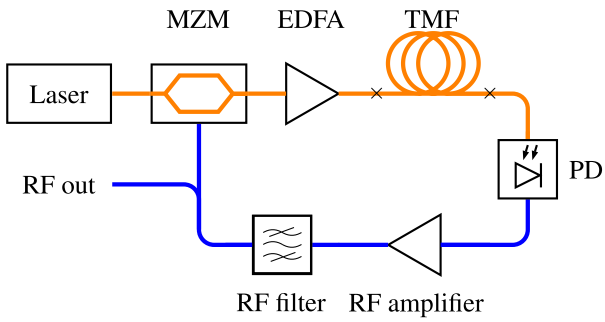

Figure 1: Simplified schematic of an optoelectronic oscillator adopting a two-mode fiber in the feedback loop

filtered. The resulting signal is a high purity carrier, used as both system output (indicated with "RF out") and feedback signal, the latter modulating the laser source. Notice that the optical path does not involve optical filters. In fact, it is our intention to address the problem of filtering out spurious harmonics without involving such a filter.

2 Background

The working principle of a dual-loop OEO is thoroughly described in [3]. Considering the case in which the modulus of the open-loop gain is larger than unity, the oscillation condition at frequency f_{osc} is achieved if

$$f_{\text{osc}} = \frac{m_1}{\tau_1} = \frac{m_2}{\tau_2} \tag{1}$$

where m_1 and m_2 are integers, and τ_1 and τ_2 denote, respectively, the loop delays of the two modes under consideration.

Let $n_{g,01}$ and $n_{g,11} > n_{g,01}$ be the group indices of the LP_{01} and LP_{11} modes, respectively, propagating in a TMF of length L. By definition of group index, the delays associated to the two modes are $\tau_1 = n_{g,01}L/c_0$ and $\tau_2 = n_{g,11}L/c_0$, c_0 being the speed of light in vacuum. Equation (1) can therefore be written as

$$f_{\text{osc}} = \frac{m_1 c_0}{n_{g,01}L} = \frac{m_2 c_0}{n_{g,11}L}. \tag{2}$$

From (2), it immediately follows that

$$\frac{m_2}{m_1} = \frac{n_{g,11}}{n_{g,01}}. \tag{3}$$

Table 1: Test parameters

Δf_{FWHM} (kHz)	δ (Hz^{-1})
32	$4.707\,344 \times 10^{-8}$
16	$2.353\,672 \times 10^{-8}$
8	$1.176\,836 \times 10^{-8}$
4	$5.884\,180 \times 10^{-9}$
2	$2.942\,090 \times 10^{-9}$
1	$1.471\,045 \times 10^{-9}$

For a two-mode step-index fiber with refractive indices 1.450 and 1.444 and core diameter of 12 µm, at the wavelength of 1550 nm, the ratio $n_{\mathrm{g},11}/n_{\mathrm{g},01} \approx 5219/5216$. Therefore, $m_1 = 5216$ and $m_2 = 5219$ are the smallest integers satisfying (3). Consequently, according to (2), in order for f_{osc} to be 10 GHz, a length $L \approx 107.8\,\mathrm{m}$ is to be chosen. However, it has been demonstrated that full width at half maximum (FWHM) of the oscillator decreases quadratically with the loop-delay time, i.e. the fiber length [2]. Hence, a longer fiber may be selected in order to reduce the line width of the resulting carrier signal. This is always possible, provided that m_1, m_2, and L are multiplied by the same positive integer, so that the oscillation frequency remains constant [see (2)]. Moreover, as numerically demonstrated in the next section, a longer fiber results in a larger delay difference between the two propagating modes, hence achieving a better filtering of the undesired resonance frequencies in the oscillator. On the other hand, in a long fiber, undesired effects such as chirp and signal degradation due to intrinsic losses become significant. For this reason, an intuitively effective choice is to keep the value of L as low as possible. This work aims at analyzing how the value of L and the purity in the carrier signal are related to the filtering property of the proposed system.

3 Simulations

For the sole purpose of calculating the noise-to-signal ratio δ, defined below, we first consider a single-loop OEO with the desired output frequency $f_{\mathrm{osc}} = 10\,\mathrm{GHz}$, loop length $L = 100\,\mathrm{m}$, and the group index $n_{\mathrm{g}} = 1.450\,587$. For sufficiently small values of loop-delay time, it is possible to express the proportionality constant δ that relates the FWHM and the fiber length as [2]:

$$\delta = 2\pi \Delta f_{\mathrm{FWHM}} \left(\frac{n_{\mathrm{g}} L}{c_0} \right)^2 \qquad (4)$$

We then consider, as an example, the set of values of Δf_{FWHM} reported in Table 1, along with the corresponding values of δ, calculated by using (4).

We now focus on the OEO depicted in Fig. 1, assuming $f_{\mathrm{osc}} = 10\,\mathrm{GHz}$, $n_{\mathrm{g},01} \approx 1.450\,713$ and $n_{\mathrm{g},11} = 1.451\,548$. The value of L is varied from $L_{\mathrm{min}} = 107.8\,\mathrm{m}$ to $10\,780.0\,\mathrm{m}$ in steps of L_{min}. This ensures that (1) can be always verified, for any length, by conveniently multiplying m_1 and m_2 by the same integer number $p > 0$. Here, p runs from 1 to 100. In other words, (1) can be written as

$$f_{\mathrm{osc}} = \frac{p m_1 c_0}{n_{\mathrm{g},01} L_p} = \frac{p m_2 c_0}{n_{\mathrm{g},11} L_p}, \quad p = 1, 2, \ldots, 100. \qquad (5)$$

where $L_p = p L_{\mathrm{min}}$.

The spectrum of the dual-loop OEO is calculated as the product between the two spectra produced by two independent single-loop OEOs, one in which only the LP_{01} mode propagates in the TMF and one where only the LP_{11} mode is present. The FWHM of all tones is calculated by solving (4) for Δf_{FWHM}, namely,

$$\Delta f_{\mathrm{FWHM}} = \frac{\delta}{2\pi} \left(\frac{c_0}{n_{\mathrm{g}} L_p} \right)^2, \quad n_{\mathrm{g}} = n_{\mathrm{g},01}, n_{\mathrm{g},11}. \qquad (6)$$

The spectra of both tones are assumed to have a Lorentzian amplitude distribution. [2]

The effectiveness of the proposed approach as a filter for spurious tones is evaluated by measuring the simulated peak amplitude of the undesired harmonic closest to f_{osc} (see Fig. 2) as a function of L_p. This is, in fact, assumed to be the predominant unwanted harmonic.

The simulation result is plotted in Fig. 3. The figure shows that, as expected, spurious modes are better filtered when Δf_{FWHM} is low. Also, when the fiber length becomes larger than about 5 km, the improvement achieved by halving Δf_{FWHM} is constant and approximately equal to 12 dB, whereas and the curve slope is

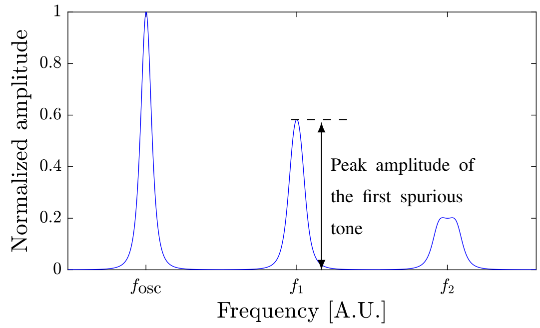

Figure 2: Spectrum of a dual-loop OEO in a region close to the central frequency f_{osc}. The frequencies of the first two higher harmonics are indicated with f_1 and f_2.

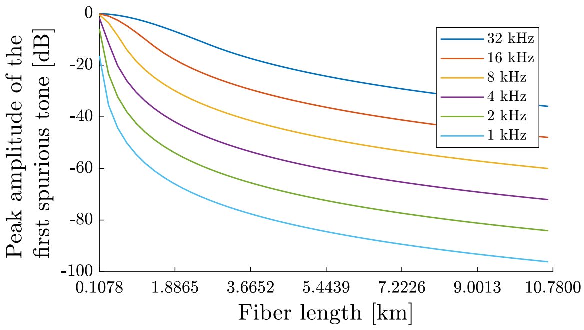

Figure 3: Peak amplitude of the spurious tone closest to the desired oscillation frequency as a function of the TMF length for selected values of the carrier FWHM.

around $3\,\mathrm{dB\,km^{-1}}$. Moreover, the impact on the system performance is much higher when the fiber length increases from its minimum up to around $5\,\mathrm{km}$. This means that increasing the fiber length may not be a good strategy to attenuate undesired harmonics when L_p becomes larger than $5\,\mathrm{km}$. In fact, as already mentioned, excessively long fibers may worsen the system performance due to attenuation and dispersion.

4 Conclusion

In this work, a preliminary study on an optoelectronic oscillator involving a two-mode fiber in the feedback loop has been conducted. The system has been analyzed as a dual-loop oscillator in which the short loop is associated with the LP_{01} mode propagating in the fiber and the long loop is associated with the LP_{11} mode.

The main goal has been analyzing the impact of the fiber length on the suppression of spurious modes. The simulated results show that, when the fiber length is close to its minimum, any small variation of its length largely affects the system filtering performance. When instead the fiber is sufficiently long, an increment in its length produces a reduction in the amplitude of the first harmonic of about $3\,\mathrm{dB\,km^{-1}}$.

The obtained results are very promising; an attenuation of the first undesired harmonic of around $100\,\mathrm{dB}$ has been achieved with a fiber spool roughly $10\,\mathrm{km}$ long, despite the assumption of a large noise in the setup.

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