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Optoelectronic Oscillator with Delay Elements in Optical and RF Domain

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Abstract — This study describes the generation of microwave signals by an optoelectronic oscillator, OEO. The delay of the OEO was made in the optical domain as well as in the radio frequency (RF) domain. The constructed OEO was proposed for embedded applications, which require low components volume, e.g., small size. Aimed at greater thermal stability and the application in embedded systems, a shorter acceptable optical fiber length was used as delay element. This enables to obtain an RF signal with the phase noise values according with the technical specifications. The total value of the OEO delay is completed with a delay in the RF domain.

The benefits of this setup include the possibility of using inexpensive components and commercially available bandpass filter. Fiber optic section with length of 200 meters, coaxial cable and a filter with 15 MHz of bandwidth were used. The output characteristics of the OEO were a microwave signal at 2.022 GHz, an intensity of 10.5 dBm and a phase noise equal to $-118.7 \text{ dBc/Hz}$ for an offset of 100 KHz and $-102.2 \text{ dBc/Hz}$ for an offset of 10 KHz.

1. INTRODUCTION

The generation of radio frequency signals in the GHz range by optical devices have a natural compatibility with optical distribution networks and the transmission of microwave signals through optical fibers \cite{1}. Early authors proposed a photonic system for microwave generation with low phase noise \cite{2–4}. The proposed system is known as optoelectronic oscillator, OEO. It converts the energy of continuous laser light into spectrally pure microwave signals \cite{2, 5}.

Starting with an optical link plus a feedback loop, different configurations of OEO has been reported \cite{6–12}. One of the disadvantages of the initial OEO design was the limitation of the electrical bandpass filter to remove unwanted frequencies’ components from the output signal. In this way, a feedback multiloop was proposed \cite{6}. As long as the length of the second loop is not an integer multiple of the first loop length, the two frequencies components will not overlap with each other. In order to solve the shortcomings of the multiloop OEO, the master-slave configuration was proposed \cite{7}. In this configuration, a short loop OEO, known as the slave, is injection locked by a longer loop OEO, known as the master. In this case, the overall system has the widely spaced frequency components of the short loop OEO, while having the phase noise performance of the longer loop OEO. In order to achieve single frequency oscillation an RF filter is used in the loop. If a larger optical loop length is used, a lower spacing would be obtained. It is therefore, difficult to design a narrow band RF filter that can sustain single frequency operation. The OEO typically has frequencies of up to tens of giga-hertz and phase noise down to $-140 \text{ dBc/Hz}$ \cite{8,9,13–15}.

In this paper, we use an OEO with a compact configuration for embedded applications, which requires low components volume, with a stable frequency signal, and phase noise values according with the technical specifications.

2. OPTOELECTRONIC OSCILLATOR — OEO

The typical layout of an OEO scheme with an external electro-optic modulator \cite{2} is presented in Figure 1.

The OEO consists of two principal sections: optical and electrical. The optical domain includes semiconductor laser module, Mach-Zehnder electro-optic modulator (MZ), optical fiber length, and photodetector module. The electrical or RF domain includes a low phase noise RF amplifier, bandpass filter, and power splitter. When the gain in the electrical section is greater than the losses, the OEO will oscillate. The electrical bandpass filter selects the frequency of oscillation \cite{10,13,16}. In such systems, the spectral purity of the microwave signal results from the length of the delay line inserted in the circuit \cite{17}.
3. OEO WITH DELAY IN THE OPTICAL AND RF DOMAIN

Unlike the literature, we propose an optoelectronic oscillator with a delay in the RF domain and not only in the optical domain.

Aiming for greater thermal stability, an optical fiber length as short as possible was used as a delay element. After the optical section an electrical section delay is added. The delay in the optical domain is made with a fiber length of 200 meters, while the delay in the RF domain is made with components and coaxial cables.

The OEO photonic circuit has the following components: DFB laser source operating at 1546 nm and output optical power of 10 mW. The MZ is a LiNbO$_3$ modulator with a bandwidth of 10 GHz and half-wave DC voltage of $V_\pi = 5.7$ V. The bandpass filter has a center frequency of 2022 MHz and the total gain is 36 dB with a total delay of 1 $\mu$s into the loop.

4. THEORETICAL ANALYSIS

If we consider the OEO as an optical link plus a feedback loop it is possible to evaluate the total gain in the feedback loop needed to generate the RF signal. Figure 2 shows an optical link.

After the optical link analysis [18, 19], it is possible to calculate the minimum gain of the feedback loop to satisfy the oscillating state requirements, agreeing with the Barkhausen’s criterion [20].

The optical gain of the optical link is given by the following equation:

$$G_T = 10 \log(g_{Tme})$$  \hspace{1cm} (1)

$$g_{Tme} = \frac{4S_{mz}^2 \cdot r d^2 \cdot R_{mz}^2 \cdot T f^2}{[R_s + R_{mz}]^2 + (\omega \cdot C_{mz} \cdot R_s \cdot R_{mz})^2 \cdot [1 + 4(\omega \cdot C_d \cdot R_l)^2]}$$  \hspace{1cm} (2)

$$S_{mz} = \frac{\pi \cdot T_{mz} \cdot P_{cw} \cdot R_s}{2 \cdot V_\pi}$$  \hspace{1cm} (3)

where $S_{mz}$ (MZ efficiency), $R_s$ (modulation source resistance), $\omega$ (angular velocity of the RF signal), $C_d$ (photodetector junction capacitance), $R_l$ (laser resistance), $r d$ (optical receptor responsivity), $C_{mz}$ (MZ capacitance), $P_{cw}$ (optical power of the laser), $T_{mz}$ (optical transmission coefficient of
the MZ), $T_f$ (optical transmission coefficient between the modulation and detection devices), $R_{mz}$ (resistance of the MZ) and $V\pi$ (half-wavelength voltage).

In Table 1, it is shown the parameters values used to obtain the optical link gain for an optical power of 10 mW, according to the Equations (1), (2) and (3).

<table>
<thead>
<tr>
<th>$R_s$ (50 $\Omega$)</th>
<th>$C_d$ (0.3 $\cdot$ 10$^{-12}$ F)</th>
<th>$T_mz$ (0.46854)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_d$ (1)</td>
<td>$C_d$ (8.33 $\cdot$ 10$^{-12}$ F)</td>
<td>$T_f$ (0.79)</td>
</tr>
<tr>
<td>$R_l$ (50 $\Omega$)</td>
<td>$P_{cw}$ (10 mW)</td>
<td>$R_{mz}$ (50 $\Omega$)</td>
</tr>
</tbody>
</table>

For an optical power of 10 mW was obtained a gain of $-31.7$ dB. The results of these calculations represent the minimum gain values for the OEO to oscillate.

The spectral noise density of the OEO output signal is:

$$S_{RF}(f') = \frac{\rho N \cdot G_A^2 / P_{cw}}{1 + |H(f')G(V_0)|^2 - 2|H(f')G(V_0)| \cos(2\pi f'\tau_d)}$$

where $f'$ is the offset frequency of the carrier, $\tau_d$ is the total circuit delay ($\tau_d = 1$ $\mu$s). $|H(f')|$ is the transfer function module considered here as a bandpass filter with center frequency of 2.022 GHz. $G_A$ is the loop gain ($G_A = 36$ dB), $P_{cw} = 10$ mW and $\rho N$ is the spectral noise density. $G(V_0) \approx 1$ and $|H(f')| \approx 1$ is a good approximation [2, 21].

In order to compare the theoretical results obtained with the experimental results, we decided to analyze the values for offset frequency point of 10 KHz and 100 KHz. For an offset frequency of 10 KHz and 100 KHz the phase noise value found is $-98.82$ dBc/Hz and $-118.67$ dBc/Hz respectively.

5. EXPERIMENTAL RESULTS

Early experiments were performed with the setup shown in Figure 1.

In order to minimize the external interferences and noise of the systems, we mounted the OEO inside a metal box, which gave us better measurements. Each stage of the circuit was mounted on one floor of the box (in order to separate the optical domain from the RF loop).

Figure 3 shows the OEO assembly in the metal box.

Figure 4 illustrates OEO output. With an optical power of 10 mW and bias of 4.8 V, an output signal with an amplitude of $10.52$ dBm and frequency of 2022 MHz is obtained.
Figure 4. Output signal of the OEO.

Figure 5 shows the OEO output with a spacing of 981 KHz between the frequencies. This spacing corresponds to a delay of 1 μs, considering the delay in the optical and RF domain. One can observe there is a difference of 60 dB between the main and secondary frequency components.

Figure 5. OEO output with a spacing of 981 KHz between the lines.

Figures 6 illustrates the experimental results for OEO, there is one marker for 10 KHz offset frequency and one for 100 KHz offset frequency point. The experimental measurement of the phase noise was $-102.2 \text{ dBc/Hz}$ at 10 KHz and $-118.7 \text{ dBc}$ at 100 KHz offset from the carrier.

Figure 7 is a plot of the phase noise as a function of the frequency offset, with the experimental and theoretical values. The results obtained in the theoretical curve are consistent with experimental data between 10 KHz and 100 KHz. There is a small difference of 4 dBc/Hz for an offset frequency of 10 KHz and the same value for 100 KHz offset when compared with the experimental value.

Some authors presented similar phase noise values to those reported in this paper, however they
Figure 6. Phase noise of the OEO. Marker 1: $-102.2$ dBc/Hz at a 10 KHz offset from carrier. Marker 2: $-118.7$ dBc/Hz at a 100 KHz offset from carrier.

Figure 7. Phase noise of the OEO with theoretical and experimental values.

did use a larger and more complex configuration with a long optical fiber length. Phase noise equal to $-90$ dBc/Hz for a 100 KHz offset from carrier and $-74$ dBc/Hz at 10 KHz or $-108$ dBc/Hz at 10 KHz offset was reported [11, 12, 21].

6. CONCLUSION

Signal generation with frequency of 2.022 GHz with an amplitude of 10.5 dBm was observed. Phase noise values in the range of $-102.2$ dBc/Hz for a 10 KHz offset from carrier and $-118.7$ dBc/Hz for a 100 KHz offset are consistent with the expectation, these values are compatible with the delay $\tau$ present in the feedback loop with better results than those obtained with configurations that are more complex. This work was conducted to embedded applications of the OEO.

REFERENCES