On a Single Loop Optoelectronic Oscillator Using Variable Centre Frequency Dynamic Filter

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Abstract

The present paper considers the influence of a variable center frequency tuned circuit replacing the narrowband RF filter in a conventional optoelectronic oscillator. The free-running amplitude and normalized frequency of such a system are derived and theoretical analysis coupled with experimental results showing good agreement are presented. Finally, the frequency control arrangement for such a system in response to an angle modulated signal is reported.

Keywords
Optoelectronic Oscillator, Mach-Zehnder Modulator, Dynamic Filter, Fiber Delay, Lock Range

I. Introduction

The Optoelectronic Oscillator (OEO) has attracted many researchers because of its ability to generate high purity low phase noise microwave and optical signal. OEO was first proposed by M Nakazawa, T Nakashima and M Tokuda [1] in 1984. The application covers a wide area of photonic and RF systems such as microwave frequency standards, radars, RF photonics and optical signal processing [2-3]. Incidentally OEO owes its origin to the delay-line oscillators of seventies. An OEO is similar to that of the Barkhausen’s oscillator. In the Barkhausen’s oscillator, the flux of electrons from the cathode to the anode is controlled by the potential on the inverting grid and thus this potential is affected by the feedback current in the anode circuit comprising a resonant network. The function of the grid is replaced by an electrical-optical (E/O) converter, the function of the anode by an optical-electrical (O/E) converter, and finally the energy-storage function of the LC circuit by a long optical delay line. Namely, the oscillator converts the continuous light energy to an RF (radio frequency) signal.

In this paper, the narrowband RF filter was replaced by a tuned circuit whose centre frequency can be varied by the application of a dc control voltage. It is worthwhile to note that the modified OEO with dynamic filter is capable of tracking the instantaneous frequency of a frequency modulated signal. The input/output governing equation for the dynamic tuned circuit along with the closed-loop equation for the OEO was derived. Expressions for the steady-state amplitude and normalized frequency was presented. Theoretical analysis coupled with experimental findings were presented and they were in good agreement. Finally, the tracking capability of the OEO with reference to an angle modulated signal was studied with particular emphasis on the variation of the lock range with injection signal strength.

II. Theoretical Analysis

If \( G_1 \) is the gain of a second order tuned circuit, then the transfer function can be written as [5-6]

\[
G(s) = \frac{G_1}{1 + Q \left( \frac{s}{\omega_c} + \frac{\omega_0}{s} \right)} = \frac{Y(s)}{X(s)}, \quad x(t), \text{ and } y(t),
\]

being the input and the output to the transfer function respectively. Again if \( \Delta \omega \) is the frequency detuning term then one can get

\[
\frac{d^2y}{dt^2} = -\frac{\omega_0}{Q} \frac{dy}{dt} - \left[ \omega_0 + \Delta \omega \right]^2 y(t) + \frac{G_0 \omega_0}{Q} \frac{dx}{dt};
\]

assuming zero initial condition. This equation is utilized for the design of the variable centre frequency tuned circuit, henceforth referred to as ‘dynamic filter’. For the single loop OEO, if the stationary \( \mu \) wave signal is of the form \( v(t) = V(t) \exp \left[ j \omega_0 t + \theta(t) \right] \);

\( G_2 \) is the gain of the RF amplifier in the OEO loop and \( v(t) \) is the RF output from the photo-detector, then the closed loop equation can be written as [4], [6]

\[
v(t) = \frac{v(t)}{G_1, G_2} = v(t) \left( 1 - \frac{\omega_0}{\omega_c} \right) \frac{1}{\omega_1, \omega_2, \omega_3} \left( j \omega_1 + \frac{\Delta \omega}{\omega_0} \right) ;
\]

where \( s = j \omega \).

Fig. 1: Conventional Single Loop OEO Using RF Filter and Modified OEO Using Dynamic Filter
It is not difficult to show that the substitution of the above results in (1) gives

\[
\begin{align*}
\frac{dV}{dt} &= \frac{\omega_o}{Q} \left[ 2GJ \left[ V(t-\tau) \cos(\omega_o \tau) - V(t) \right] \right] \\
\frac{d\theta}{dt} &= \frac{2G \omega_o}{Q} \frac{J_1}{V(t)} \frac{\cos(\omega_o \tau)}{V(t)} \sin(\omega_o \tau)
\end{align*}
\]

Similarly, the imaginary part of (2) gives the phase equation

\[
\frac{d\theta}{dt} = \frac{2G \omega_o}{Q} \frac{J_1}{V(t)} \frac{\cos(\omega_o \tau)}{V(t)} \sin(\omega_o \tau)
\]

In the steady-state, \(\frac{dV}{dt} = 0\) and using the weakly varying assumptions i.e., since ‘\(V(t)\) & ‘\(\theta(t)\)’ are slowly varying functions of time,

\[
\frac{1}{\omega_o} \left( \frac{d\theta}{dt} \right) << 1 \quad \text{and} \quad \frac{1}{V(t)} \left( \frac{dV}{dt} \right) << 1,
\]

Hence it is not difficult to show the steady-state voltage as

\[
V = 2\sqrt{2} \left( -\frac{1}{G} \cos(\omega_o \tau) \right)
\]

and the normalized free-running frequency as

\[
\frac{\omega_f}{\omega_o} = 1 + \frac{1}{1 + \frac{\Delta \omega}{\omega_o}} \left[ 1 - \frac{\tan(\omega_o \tau)}{G} \right]
\]}
The experimental validations and the theoretical verifications were obtained using MATLAB SIMULINK and MATHCAD™ respectively. The proposed dynamic filter was inserted in place of the narrowband RF filter in a conventional single loop OEO shown in Fig. 1. The frequency response of the dynamic filter was shown in Fig. 2, and Fig. 3 shows the linear variation of the centre frequency of the dynamic filter with the frequency detuning \( \Delta f \) Fig. 2 shows that the dynamic filter is having a peak response at 12.0 MHz. To observe the linear variation of the detuning frequency with the shift in centre frequency of the dynamic filter, an RF gain of 2.0 and quality factor of 76.9 was used. In fig.5, the centre frequency of the OEO was 11.92 MHz, fibre delay was 10 nanosecond and the quality factor of the dynamic filter was 76.9, while in Fig. 6, a frequency deviation of 11.9 MHz was chosen. While taking the Fast Fourier transform of the RF output obtained from the single loop OEO shown in Fig. 4, an overall gain of 6.0 and a frequency deviation of 0 MHz were used. Figures 7 and 9 are the experimental verifications of the theoretical results shown in Fig. 6 and Fig. 5 respectively. The experimental validation of (5) was shown in Fig. 8. Moreover in Fig. 6 the variation of normalized frequency with delay was compared with that of a conventional OEO incorporating band-pass filter. Finally, the modified OEO is synchronized with a frequency modulated wave. The dynamic filter adjusts its centre frequency in such a way that the centre frequency becomes equal to the instantaneous frequency of the modulated signal. Once synchronized, the variation of the lock range of the OEO with injection amplitude was shown in Fig. 10. Table 1 presents the experimental data for Fig. 7 and 8 respectively, while table 2 was that for Fig. 9.

Table 1: Experimental data

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<thead>
<tr>
<th>Fiber delay in nsec</th>
<th>Normalized amplitude</th>
<th>Normalized frequency</th>
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<tr>
<td>1.0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3.0</td>
<td>0.989</td>
<td>0.999</td>
</tr>
<tr>
<td>5.0</td>
<td>0.97</td>
<td>0.998</td>
</tr>
<tr>
<td>7.0</td>
<td>0.94</td>
<td>0.997</td>
</tr>
<tr>
<td>9.0</td>
<td>0.89</td>
<td>0.995</td>
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<tr>
<td>10.0</td>
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<td>0.994</td>
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Table 2:

<table>
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<th>Frequency detuning in MHz</th>
<th>Normalized frequency</th>
</tr>
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<tr>
<td>0.5</td>
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</tr>
<tr>
<td>1.0</td>
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<td>1.5</td>
<td>1.124</td>
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<td>2.0</td>
<td>1.166</td>
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<tr>
<td>2.5</td>
<td>1.207</td>
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Fig. 10: Experimental Verification of Lock Range With Injection Amplitude

IV. Conclusion
We have theoretically and experimentally demonstrated the performance of a single-loop OEO using dynamic filter in place of a conventional RF filter. System equations of the modified OEO have been derived. Theoretical analyses coupled with experimental findings are in good agreement.

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References