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Harmonic distortion and power relations in a single loop optoelectronic oscillator

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ABSTRACT

This paper begins with a review of the work in the field of single loop optoelectronic oscillator. Detailed theoretical investigation of the system incorporating an injection locked oscillator in place of the conventional bandpass filter is presented. Power relations and harmonic distortions of the oscillator are calculated. Experimental results showing in good agreement with theoretical predictions are given.

1. Introduction

Recently, a good deal of work on a single loop optoelectronic oscillator (OEO) has been reported (Mukherjee [3,5], Chatterjee [6], Biswas [4], Zhou and Blasche [12], Yao and Maleki [8–11]) and very little effort has been directed towards the development of a systematic analytical approach for studying the output power relationship and harmonic distortions of an OEO. Biswas [13] presented a derivation for AM to PM conversion in an injection synchronised oscillator.

In the last fifteen years or so, generation of spectrally pure microwave and mm-wave has been achieved using optical schemes. The most widespread approach is based on the opto-electronic oscillator where high Q optical cavities with extremely low loss are used with optoelectronic feedback loops. The generic OEO consists of a light source (usually a laser), light modulator, optical cavity and a photodetector; the output of which is fed back to the modulator to achieve a closed-loop configuration (Fig. 15). This feedback loop can generate self-sustained oscillation if its overall gain is greater than the loss, and the circulating waves add up in phase. The former requirement can be met with insertion of gain in the loop and, the latter, by controlling the phase. Since the loop can support waves circulating many times, the oscillator is fundamentally multi-mode, with the mode spacing determined by the free spectral range of the cavity. By adding a filter in the loop with a prescribed centre frequency, the output of the oscillator can be obtained at that frequency. In this way, any frequency supported by the bandwidth of the components can be generated. Now, this multi-mode oscillation can be suppressed if the band-width of the filter in the loop is narrow enough so that only a single mode of oscillation survives in the loop. Such a narrow-band filter, however, is not practical, especially when the length of the fibre is long and the operating frequency is in the microwave and mm-wave range. One approach to mitigate this problem is to replace the RF band-pass filter by an injection locked oscillator in the loop. The synchronised oscillator ignores any signal that lies outside the locking range. So the trick is to synchronise the centre frequency of the injection locked oscillator with that of the free running frequency of the OEO.

In this paper we present a conventional oscillator and its amplitude governing equation along with the steady state value is derived. The phase plane portrait of the oscillator reveals that the oscillator output voltage is convergent implying the stability of the system. Now, the RF band-pass filter is replaced by this oscillator with injection synchronisation. It is worthwhile to mention that the net input to RF adder in the OEO consists of three signal components: (i) output voltage from the Mach–Zehnder modulator (MZM), (ii) output voltage from the injection synchronised oscillator and (iii) synchronising signal. The steady state amplitude and the free-running frequency are derived theoretically and

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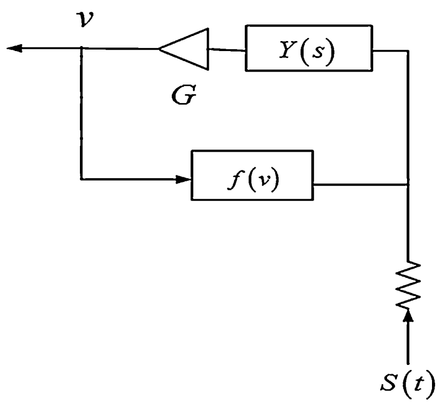

Fig. 1. Injection synchronised oscillator.

experimental results showing in good agreement are provided. RF output power relations as a function of input modulation index from the OEO are presented. Finally, the intermodulation distortion terms have been calculated and it has been found that in contradistinction to an injection synchronised oscillator [14], the second order distortion does not vanishes, but it can be made smaller by judiciously selecting the effective quality factor of the injection synchronised oscillator.

2. Conventional oscillator

A nearly sinusoidal oscillator may be looked upon as a device that generates an almost sinusoidal function of time. Thus it is a regenerative feedback device that derives its required input from its own output either by way of internal feedback mechanism or through an external feedback network connecting its output to the input port. Thus, whatever be the type of nearly sinusoidal oscillators, it is always a positive feedback device incorporating a frequency selective network to pick up the desired frequency of oscillation and a limiter type non-linear element to control the growth of oscillation to a suitable level. Such an oscillator (with $S(t)=0$) is shown in Fig. 1 and the closed loop equation is given by [1,2,7] $f(v)=1/G.Y(s)$, where the cubic type of non-linearity is chosen as $f(v)=a_1v-a_3v^3$. Again the transfer function of the frequency selective network is $1/Y(s)=1+R_0(sC_0+(1/sL_0))=1+Q((s/\omega_0)+(\omega_0/s))$, where $\omega_0=1/\sqrt{L_0C_0}$ and $Q=R_0/\omega_0L_0$. Now, it is not difficult to show that for the real and the fundamental component of the voltage, one gets

$$a_1v-a_3v^3=\frac{1}{G}\left[1+Q\left(\frac{s}{\omega_0}+\frac{\omega_0}{s}\right)\right]=\frac{2Q}{G\omega_0V(t)}\frac{dV}{dt}$$
$$\frac{dV}{dt}=\left(\frac{\omega_0G}{2Q}\right)\left[a_1-\frac{3}{4}a_3V^2(t)\right]V^2(t) \tag{1}$$

Steady state amplitude is $V|_{steady}=\sqrt{4a_1/3a_3}=3.651$ with $a_1=1$ and $a_3=0.1$. This result also follows from the solution of Eq. (1) as shown in Fig. 4.

For an injection synchronised oscillator shown in Fig. 1 (with $S(t)\neq 0$), the closed loop equation [1,2,7] is

$$[f(v)+S(t)]=\frac{v}{G.Y(s)} \tag{2}$$

3. Amplitude and phase governing equations of OEO

In a single loop optoelectronic oscillator (OEO) we begin with the assumption that despite the presence of the strong non-linearity due to Mach–Zehnder (MZM) modulator within the loop, there is an existence of stationary amplitude of the microwave oscillation of the form $v_i(t)=V(t)\exp j[\omega_1t+\theta(t)]$, '$\theta(t)$' arises because in the unlocked driven case the RF output is simultaneously amplitude and phase modulated, 'G_1' is the gain of the RF amplifier in the OEO loop, '$v_0(t)$' is the RF output from the photo-detector, $S(t)=E_0\exp[j\omega_1t]=\frac{E_0v_i(t)}{V(t)}\exp[-j\theta(t)]$ is the synchronising signal and 'GG_1' is the overall gain, then

$$[v_0(t)+S(t)+f(v_i)]=\frac{v_i}{G.G_1.Y(s)} \tag{3}$$

$$\frac{N[V(t-\tau)]}{V(t)}e^{-s\tau}+\frac{E}{V(t)}e^{-j\theta(t)}+\frac{f(v_i)}{v_i}=\frac{1}{G.G_1}\left[1+Q\left(\frac{s}{\omega_0}+\frac{\omega_0}{s}\right)\right]$$

where

$$s=j\omega=\frac{1}{V(t)}\frac{dV}{dt}+j\left[\omega_1+\frac{d\theta}{dt}\right];\quad \frac{1}{s}\cong\frac{1}{j\omega_1}+\frac{1}{\omega_1{}^2}\left[\frac{1}{V(t)}\frac{dV}{dt}+j\frac{d\theta}{dt}\right]$$

The output voltage of the photo detector when the output of the MZ modulator shines on it will be $V_0(t)=\rho RP(t-\tau)$; where 'ρ' is the sensitivity, 'τ' is the fibre delay given by nL/c, with 'L' is the length of fibre, 'c' is the speed of light, 'n' is the fibre refractive index and 'R' is the output impedance of the photo-detector. Hence using the above arguments, it is not difficult to show that

$$V_0(t)=V_{ph}\left[\begin{array}{l}1-\eta\sin\left(\frac{\pi V_B}{V_\pi}\right)\left\{J_0\left(\frac{\pi V(t-\tau)}{V_\pi}\right)+2\sum_{m=1}^{\infty}J_{2m}\left(\frac{\pi V(t-\tau)}{V_\pi}\right)\right.\\ \left.\quad\times\cos[2m\omega(t-\tau)]\right\}\\ -2\eta\cos\left(\frac{\pi V_B}{V_\pi}\right)\times 2\sum_{m=0}^{\infty}J_{2m+1}\left(\frac{\pi V(t-\tau)}{V_\pi}\right)\\ \quad\times\sin[(2m+1)\omega(t-\tau)]\end{array}\right]$$

where $V_{ph}=\alpha R\rho P_0/2$. It is to be noted that the OEO is a regenerative circuit and it incorporates a limiter type non-linear element. Again, it is known that the highest component of the spectrum attenuates out the smaller components and only the highest component is sustained in the loop. Hence with the growth of oscillation amplitude, the effective quality factor (Q_{eff}) of the tuned RF circuit becomes narrower and automatically rejects the other modes. Thus the output of the MZ modulator is seen to be

$$\begin{aligned}v_0(t)&=-2\eta V_{ph}\cos\left(\frac{\pi V_B}{V_\pi}\right)J_1\left(\frac{\pi V(t-\tau)}{V_\pi}\right)\sin[\omega(t-\tau)]\\&=\frac{N(V(t-\tau))}{V}\exp(-s\tau)v_i(t)\end{aligned} \tag{4}$$

In absence of sync. signal ($S(t)=0$), i.e., for the free running case

$$\begin{aligned}&G.G_1\left[\frac{N[V(t-\tau)]}{V(t)}e^{-s\tau}+\left(a_1-\frac{3}{4}a_3V^2(t)\right)\right]-1\\&=\frac{Q}{\omega_0}\left(\frac{1}{V}\frac{dV}{dt}+j\omega_0+j\frac{d\theta}{dt}\right)+Q\omega_0\left[\frac{1}{j\omega_0}+\frac{1}{\omega_0^2}\left(\frac{1}{V}\frac{dV}{dt}+j\frac{d\theta}{dt}\right)\right]\end{aligned}$$

Real part gives

$$\begin{aligned}\frac{dV}{dt}&=\frac{\omega_0}{2Q}\left\{G.G_1V(t)\left[\frac{N[V(t-\tau)]}{V(t)}\cos\omega_0\tau\right.\right.\\&\left.\left.\quad+\left(a_1-\frac{3}{4}a_3V^2(t)\right)\right]-V(t)\right\}\end{aligned} \tag{5}$$