Generation of High Stability Microwave Signal using Optoelectronic Oscillator based on Long Fibre Delay Line

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Abstract: An optoelectronic oscillator based on long fibre delay line to generate high stable microwave signal has been investigated and implemented experimentally. Mathematical model for this oscillator has been proposed. The experimental results are taken for different delay line lengths (2.1 Km, 4.2 Km and 6.6 Km respectively). The generated signal has a narrow bandwidth (less than 200 Hz) at carrier frequency 2.31 GHz and its phase noise is less than -80 dBc/Hz at 1 KHz offset. Comparison of the experimental results and analytical ones has been done. A critical length (Lc) concept of the used fibre delay line has been introduced as a design parameter for the proposed optoelectronic oscillator.

1 INTRODUCTION

There are many oscillator types like LC oscillator (Van der Pol, 1920; Van der Pol, 1934), cavity based oscillator (Ishihara et al., 1980.) and atomic oscillator (Siegman and Hagger, 1964), which provide different degrees of stability and purity of the generated signal at different frequency ranges. Stability of the output signal mainly depends on using energy storage element in the oscillator which is frequency dependent.

Another important type of oscillators used widely now is the electronic oscillator (based on transistors), its stability is improved considerably using high quality factor resonators like quartz crystals (Parzen, 1983; Halliburton et al., 1985) and dielectric cavities.

The quartz crystals resonator is the best choice, as it gives the highest stability at room temperature. But it has only a limited range of frequency tuning. Microwave signals are out of this range, so it can't be generated using this method.

Another type of oscillator is based on use of electric delay lines, as the delay time is equivalent to the energy decay time. But if coaxial cable is used, it requires high power to overcome the losses of long cable and it will be heavy and takes a large space.

Optoelectronic oscillator is another type of oscillators that uses optical signals to benefit from the high performance of optical components and very low loss and weight of optical fiber compared to coaxial cables. It can generate microwave frequencies with the ability of frequency tuning.

The first technique used in this field is based on the use of long fiber delay line to stabilize the microwave oscillator (Yao and Maleki, 1994; Yao and Maleki, 1996a; Yao and Maleki, 1996b). Another technique can be used by replacing the long fiber delay line by a short fiber ring resonator (FRR), which provides high quality factor and high stability compared to the generated signal using the first technique. FRR technique requires strict control on the ring temperature (Yariv, 2000; Yariv, 2002; Merrer et al., 2008).

New technique based on Brillouin selective side band amplification has been introduced recently. Brillouin oscillator doesn't need narrow band pass microwave filter neither microwave amplifier. On the other hand this oscillator requires a laser source with very narrow spectral width, high output power as well as it requires long fiber length (Yao, 1997; Li et al., 2013; He et al., 2016), see APPENDIX A

Each technique has its unique features. The recent researches in this field show a phase noise as low as –92.69 dBc/Hz at 10 kHz offset frequency from the oscillation frequency (2.26 GHz) carrier using optical delay line of 25.24 km and a Q factor of 2.04×10^9 (Correa-Mena et al., 2017), there is other technique generate two tone signals in a range from 4 GHz to 12 GHz with phase noise about -105 dBc/Hz at 10 kHz offset frequency from the oscillation frequency

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(9.95GHz and 10.66 GHz) (Gao et al., 2017) . In this workk we get better phase noise -104 dBc/Hz at 10 kHz offset frequency from the oscillation frequency (2.31 GHz) carrier using shorter optical delay line of 6.6 km and a lower Q factor of 0.019×10^9.

In this paper, microwave oscillator based on the first technique has been analysed and implemented.

The rest of this paper is organized as follows: system model is presented in section 2; experimental results have been investigated in section 3. The influence of optical fiber length on the oscillator stability is given in section 4 and finally, the conclusion is presented in section 5.

2 SYSTEM MODEL

2.1 Main Parameters of Optoelectronic Oscillator

The proposed system is shown in Fig.1. Electrical signal applied to Mech-Zender modulator is driven from the microwave filter. At the beginning this signal is coming from noise, the loop gain is changing till the oscillation is sustained, in this case input to the Mech-Zender modulator will be the microwave signal.

Light from a laser source (Po(t)) is introduced into an electro-optic modulator; the output modulated signal (P(t)) is passed through the fibre delay line.

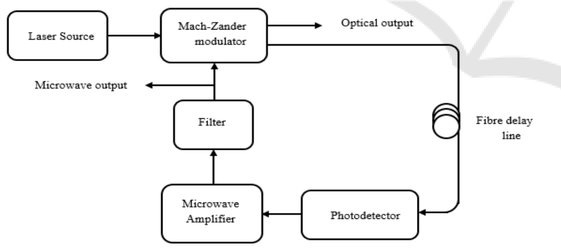

Figure 1: Optoelectronic oscillator structure.

Then, the output is detected by a photodetector. The output of the photodetector is amplified and filtered, then applied to the Mach-Zender modulator (Vin(t)), the electrical input voltage is related to the optical output power from the modulator by (1). (Chang, ed., 2007)

$$P(t)=\alpha P_o(t)[1+\eta \sin(\pi(V_{in}(t)+V_B)/V_\pi))]/2 \quad (1)$$

As (α) is the fractional loss of the modulator, (η) is the extinction ratio of the modulator, (V_B) is the bias voltage and (V_π) is the half wave voltage of the modulator. Assuming the input signal is sinusoidal wave with oscillation frequency (ω). The output microwave signal (V_{out}) is related to the modulated signal (P(t)), the responsivity of the detector (R), the load resistance (R_L), the amplifier gain (G_A), the loss of the fibre (α_f), the fibre length (L) and the absolute value of the filter transmission function (|F(ω) |)by (2).

$$V_{out}=R.R_L.G_A.\ |F(\omega)|P(t)\ e^{-\alpha_f L} \quad (2)$$

The quality factor of the generated signal (Q) depends on the quality factor of the loop delay line (Q_D), the delay time of the fiber line (τ) and the input noise to signal ratio (δ) of the oscillator as given by (3).

$$Q = Q_D.\ \tau / \delta \quad (3)$$

The delay time offered by the fiber line depends on the refractive index of the fiber (n), the fiber length (L) and the speed of light in free space (c) as shown in (4).

$$\tau = nL / c \quad (4)$$

The quality factor of the loop delay line (Q_D) depends on the delay time inside fiber line (τ)and the oscillation frequency (f), the input noise to signal ratio (δ) which depends on the equivalent input noise density injected into the oscillator (ρ_N), the oscillation power (P_{Osc}) and the total gain (G_A), as given in (5) and (6) respectively.

$$Q_D = 2\pi f\ \tau \quad (5)$$

$$\delta = \rho_N.G_A/P_{Osc.} \quad (6)$$

This technique requires a very long fibre delay line (in the kilometre range) to satisfy high quality factor and low phase noise, this means small mode spacing as the free spectral range (FSR) between oscillation modes is the inverse of the delay time in the fibre line as described by (7). So, a microwave filter with narrow bandwidth is required to select the oscillation mode.

$$FSR = 1/\tau \quad (7)$$

The small FSR problem (as a result of long fibre delay line) can be solved by using two fibre loops acts as short and long cavities to select a single operation mode (Smith, 1972). But this technique increases the size and the complexity of the system.

The output of optoelectronic oscillator may be obtained either directly as a microwave signal, or as an optical signal. It is characterized by high stability and low noise which is achieved by using optical component that are characterized by high speed, high efficiency and better performance than electrical components.

Optoelectronic oscillator utilizes the transmission characteristics of an electro optic modulator with the fibre delay line to convert light energy into stable microwave signal.

The oscillation frequency is determined by the filter characteristics and the fiber delay line length as the oscillation frequency (f) depends on the mode number (k) and the delay time inside fiber line (τ) is given by (8).

$$f = k / \tau \tag{8}$$

The 3- dB bandwidth of each fiber delay line (Δf) is given by (9).

$$\Delta f = \rho_N . G_A^2 / (2\pi\tau^2 p_{Osc}) \tag{9}$$

The phase noise (L_{Osc}) at a certain frequency offset (f_m) is related to the quality factor (Q), the oscillation frequency (f) and the spectral density of the amplifier phase fluctuations ($\Delta Ø_A$), and the ratio between the phase noise using different lengths lead to different 3-dB bandwidth and amplifier phase fluctuations are given by (10) and (11) respectively.

$$L_{Osc}(f_m) = (f / (2^{1.5}.Q.f_m))^2.(\Delta Ø_A)^2 \tag{10}$$

$$L_{osc1}(f_m) - L_{osc2}(f_m) = 20\log[(\Delta f_1)/(\Delta f_2)] + 20\log[(\Delta Ø_{A1})/(\Delta Ø_{A2})] \tag{11}$$

2.2 Critical Fibre Delay Line Length

The 3-dB bandwidth (Δf) of the generated signal is inversely proportional to the optical fibre length square as shown in (4) and (9). The equivalent input noise density injected into the oscillator (ρ_N) is the sum of the thermal noise (ρ_{th}), shot noise (ρ_{sh}) and the laser relative intensity noise (ρ_{RIN}) as given in (12).

$$\rho_N = \rho_{th} + \rho_{sh} + \rho_{RIN} \tag{12}$$

The shot noise and the relative intensity noise depend on the photocurrent (I_{ph}), the load resistance (R_L) the electron charge (e) and the relative intensity noise of the laser (N_{RIN}) as shown in (13) and (14) respectively.

$$\rho_{sh} = 2eR_LI_{ph} \tag{13}$$

$$\rho_{th} = N_{RIN}R_L(I_{ph})^2 \tag{14}$$

The photocurrent is related to the output modulated signal (P(t)), the responsivity of the detector (R), the loss coefficient of the fibre (α_f) and the fibre length (L) by (15)

$$I_{ph} = RP(t)e^{-\alpha_f L} \tag{15}$$

The total gain (G_A) is related to the amplifier gain (G_{Ao}), the loss of the fibre (α_f) and the fibre length (L) by (16)

$$G_A = G_{Ao}\, e^{-\alpha_f L} \tag{16}$$

The oscillation power (P_{Osc}) is related to the output oscillation voltage (V_{out}) and the load resistance (R_L) by (17)

$$P_{osc} = (V_{out})^2 / R_L \tag{17}$$

The previous equations show the effect of the fibre delay line length (L) in the main parameters of the 3-dB bandwidth (Δf). As the length increases, some of the parameters increase and others decrease. This leads to decrease of the rate of change of the 3-dB bandwidth (d (Δf)/d) with increasing (L), (d (Δf)/dL) is given by (18)

$$d(\Delta f)/dL = (G_A)^2.c^2\{[d(\rho_N)/dL]\, L - 2\rho_N\}/(2\pi.n^2.p_{Osc}\,.L^3) \tag{18}$$

The rate of change of (Δf) versus the fibre length (L) is decaying fast as (L) exceeds a certain value. We may define the fibre length at which the absolute value of the rate of change of 3-dB bandwidth |d (Δf)/dL| reaches 1 Hz/Km as a critical fibre length of this oscillator. This critical value may be taken as a system parameter (L_C).

For a given equivalent input noise density injected into the oscillator (ρ_N), the oscillation power (P_{Osc}), the amplifier gain (G_A) and the refractive index of the used fibre "n".There will be a specific value for (L_C). The designer of this oscillator will choose the delay fibre line length based on this value where longer length will add costs without considerable gain in reducing the 3- dB bandwidth (Δf).

3 EXPERIMENTAL RESULTS

Optoelectronic oscillator has been implemented using free bias Mach-Zander modulator, microwave filter at central frequency 2.31 GHz with three dB bandwidth of 10 MHz using different fibre delay lengths (2.1 Km, 4.2 Km and 6.6 Km respectively).

The experimental results agree with the expected ones for the main three parameters. First parameter is the, frequency spectral range (FSR) which decreases as the fiber delay line length increases (Eq. (7)). Second parameter is the three dB bandwidth (Δf) which decreases too as the fibre delay line length increases (Eq. (9)). Third one is the oscillation frequency phase noise (L_{Osc}(fm)) which becomes better with increasing the fibre length which determines the quality factor (Q) (Eq. (10)).

The output spectrum contains several modes. The number of these modes depends on the free spectral range value (FSR) and the filter bandwidth. Recall that (FSR) is proportional to the inverse of the fibre delay line length (L).

The output microwave signal using 2.1 Km fibre delay line with span 300 KHz is shown in Figure 2, where Figure 3 shows the oscillation mode with span 20 KHz.

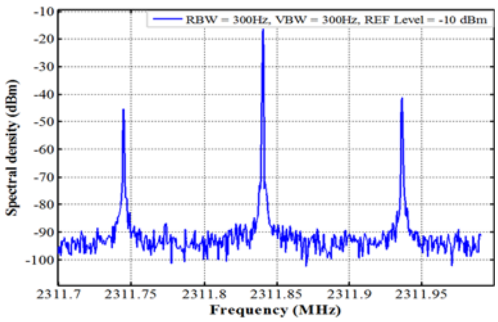

Figure 2: Output signal using 2.1 Km fibre delay line (Span 300 KHz).

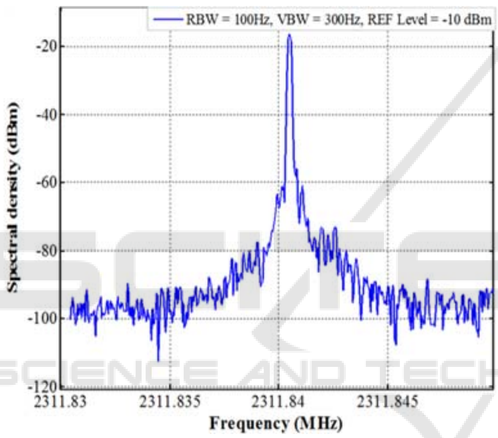

Figure 3: Oscillation mode using 2.1 Km fibre delay line (Span 20 KHz).

Using fibre length of 4.2 km, the output spectrum is shown in Figures. 4 and 5. For optical fibre length of 6.6 km, the output spectrum is illustrated in Figure 6.

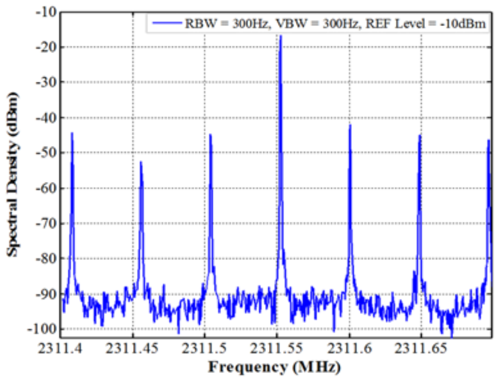

Figure 4: Output signal using 4.2 Km fibre delay line (Span 300 KHz).

As shown in Figure 2 and Figure 4, the mode spacing between the modes decreases from 95.2 KHz using 2.1 Km to 47.6 KHz using 4.2 Km and the oscillation side band suppression ratio about 25 dB. The oscillation frequency using different lengths is changed by a small amount as a result of the bandwidth of the used filter and as it must be a multiple of the (FSR).

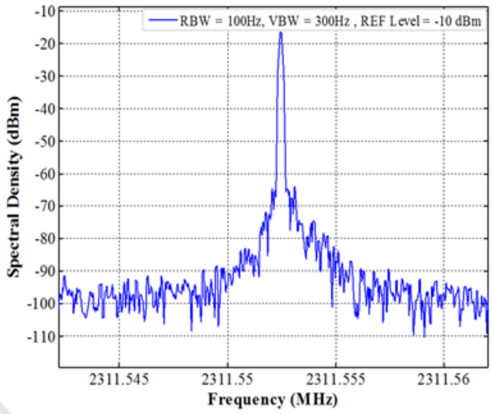

Figure 5: Oscillation mode using 4.2 Km fibre delay line (Span 20 KHz).

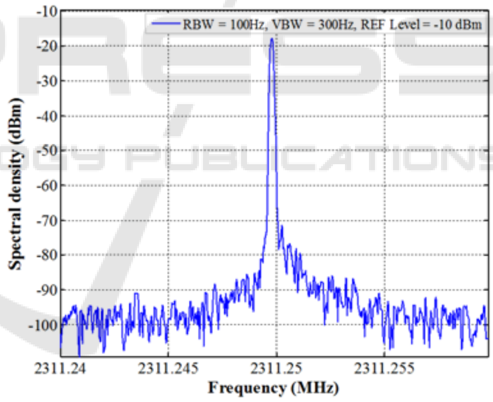

Figure 6: Oscillation mode only using 6.6 Km fibre delay line (Span 20 KHz).

The used laser (Agilent 81940A), the modulator is Mach-Zander modulator (JDSU: 2.5 Gb/s Bias-Free Modulator with Integral Attenuator), the detector is avalanche photodiode (OF3240N-MS-YT) with gain about 24 dB, the filter is cavity band pass filter (DSC-2310B-10M01) with 3dB bandwidth 10 MHz and the results are taken using RF spectrum analyser up to 3GHz (R&S FSP 9k-3G).

4 THE INFLUENCE OF OPTICAL FIBER LENGTH ON THE OSCILLATOR STABILITY

Table 1 and 2 shows the main parameters and performance parameters, respectively of the optoelectronic oscillators using different optical fibre lengths.

Table 1: Oscillator parameters comparison using three different fibre delay lines.

fibre delay line (Km)	Oscillation frequency (MHz)	Measured output Power (dBm)	FSR (KHz)
2.1	2311.8405	-16.4	95.2
4.2	2311.5524	-16.4	47.6
6.6	2311.2498	-17.86	30.3

Table 2: Oscillator performance parameters comparison using three different fibre delay lines.

fibre delay line (Km)	Measured Δf(3dB) (Hz)	Phasenoise [L_{Osc}(1KHz)] (dBC/Hz)	Phasenoise [L_{Osc}(10KHz)] (dBC/Hz)
2.1	150	-80	-100
4.2	130	-82	-101.5
6.6	120	-84	-104

The experimental results are in good agreement with the expected ones which have been calculated using the presented system model; whereas the length increases the -3 dB bandwidth and the phase noise at certain offset frequency decrease.

The measured change in -3dB bandwidth is 20 Hz (150Hz using 2.1 Km drops to 130 Hz using 4.2 Km) where this change drops to only 10 Hz (when switching from 4.2 Km to 6.6 Km). This agrees with the results given by the system model, whereas as the fibre delay line (L) increases, the rate of change of -3 dB bandwidth change decays.

5 CONCLUSIONS

We have successfully implemented a high stability microwave oscillator based on long fibre delay line. System model has been presented. The expected effect of the optical fibre length on the main parameters has been tested and verified. Investigation of analytical and experimental results leads to what we call critical fibre length (L_C) which depends on the main specifications of the proposed oscillator. Using fibre length (L) exceeding (L_C) the improvement of 3-dB bandwidth (Δf) is almost negligible. The results based on this model are compared to the experimental ones and a good agreement is observed. Our future work is to use several fibre delay line lengths (seven at least) and investigate in more depth the effect of increasing the fibre length over the critical one. Future work may be extended to use other techniques based on the fibre ring resonator and Brillouin selective side band technique in order to compare these three techniques.

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APPENDIX A

The Brillouin threshold is given by (Li et al.., 2013):

$$P_{th} = 21\frac{A_{eff}}{g_B L_{eff}} \tag{A1}$$

where

A_{eff}: the effective cross section area of the fiber core.

L_{eff}: the efective length of the fiber.

g_B: the Brillouin gain coefficient, which is given by

$$g_B = \frac{4\pi\gamma 2}{\mathrm{n_0}\lambda^2 \mathrm{c}\rho_0 \mathrm{v_a}}.\frac{1}{\Delta\nu_o} \tag{A2}$$

where

γ: the electrostrictive coefficient.

n_o: the refractive-index.

λ : the wavelength of the laser signal.

c: the light speed in free space.

ρ_0: density of the scattering medium.

V_a: velocity of the induced (acoustic) wave in the medium

$\Delta\nu_o$: the spectral linewidth of the pump laser.

It's clear the effect of the spectral linewidth of the pump laser on the threshold pump power of Brillouin beam.