Charge Pump DPLL to Operate at High Frequencies

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ABSTRACT

This work presents a pre-charge type DPLL that can be used as a clock recovery circuit in SDH/SONET communication protocols at 622 MHz. It is presented the phase/frequency detector which can operate equally at low and high frequencies. Each block of the DPLL is described, calculated and simulated. It is also presented the stability criteria and analysis of the DPLL and its final layout. The main feature of this work is the quick synchronization time of the DPLL due to the inclusion of an initialization circuit.

Keywords: PLL, DPLL, PFD, VCO, Synchronization.

1. INTRODUCTION

In synchronous communication systems, the receiver should be able to recover the clock signal from the incoming message. This is required in order to sample and process the incoming data at the proper time. Therefore, the receiver should be able to have a perfect copy of the clock signal used by the transmitter. The circuit used to recover the clock signal is the clock recover circuit.

The mostly used circuit to recover the clock signal is the Phase Locked Loop - PLL [Best,1993; Wolaver,1991]. The PLL compares the phase and/or frequency between the reference signal and a signal generated by the PLL circuit itself. If the reference signal and the self generated signal have the same phase/frequency, they are synchronized, and in this case, the signal generated by the PLL is used as a synchronization signal in the receiver.

This work presents an implemented Digital Phase Locked Loop - DPLL which has quick synchronization and it is implemented by a reduced number of transistors. This DPLL may be used in Synchronous Digital Hierarchy - SDH and Synchronous Optical Network - SONET network protocols operating at 622MHz.

2. CHARGE PUMP DPLL

The DPLL [Paemel,1994] is composed basically of four blocks, namely the Phase Frequency Detector - PFD, the charge pump circuit, the low-pass loop filter and the Voltage Controlled Oscillator - VCO, as shown in Figure 1.

Figure 1 DPLL block diagram.

The PFD is a sequential phase/frequency detector [Gardner,1979]. The PFD has the following valid states as output:

- Up= 0 and Down= 0 indicad high impedance state where $F_{ref} = F_{vco}$.
- Up= 0 and Down= 1 indicad Down pulse generated where $F_{ref} < F_{vco}$ or θ_{ref} leading θ_{vco} .
- Up= 1 and Down= 0 indicad Up pulse generated where $F_{ref} > F_{vco}$ or θ_{ref} lagging θ_{vco} .

The PFD needs a charge pump circuit, as indicated in Figure 1. The charge pump is basically an electronic switch that injects (drains) a current I_p in(from) the loop filter, depending on the pulse generated by the PFD. The charge pump conducting interval t_{on} is given by:

$$t_{on} = \frac{|\theta_e|}{\omega_{in}}. \quad (1)$$

where θ_e represents the phase/frequency between the reference and the VCO signals, and ω_{in} represents the angular frequency of the incoming signal.

The current injected (drained) by the charge pump circuit, in each cycle, is given by:

$$i_d(t) = \pm I_p \left(\frac{t_{on}}{T} \right) = \pm I_p \left(\frac{|\theta_e|}{2\pi} \right). \quad (2)$$

The gain of the charge pump PFD is given by:

$$K_d = \frac{I_p}{2\pi}. \quad (3)$$

The VCO must produce a signal that has an output frequency as function of the voltage produced by the loop filter and its should have the same phase and frequency of the reference signal.

Since the signal angular frequency is given by the derivative of the signal on the time, then the VCO controlling equation is:

$$\frac{d\theta_0(t)}{dt} = \omega_0 + K_0 V_c(t). \quad (4)$$

where $\theta_0(t)$ represents the phase of the VCO signal, ω_0 represents the VCO angular frequency, and K_0 represents the gain of the VCO, given in [rad./V.s].

Therefore, from equation (4), the VCO frequency shift caused by the system controlling voltage is given by (in the frequency domain):

$$\theta_0(s) = K_0 \frac{V_c(s)}{s}. \quad (5)$$

The signal produced by the PFD is composed of a DC level, proportional to the phase/frequency error of the input signals, and by high frequency components. Since this signal is used as the VCO controlling voltage, the high frequency components must be eliminated using a low pass loop filter [Gardner,1980; Encinas,1993; Keese,1996]. The loop filter is also responsible to eliminate any ripple in the DPLL, which could take the VCO to saturation, forcing the DPLL to loose the synchronism.

Figure 2 shows the DPLL block diagram. From the figure, the closed and open loop transfer functions are, respectively:

$$\frac{\theta_o(s)}{\theta_{in}(s)} = \frac{K_o K_d Z_f(s)}{s + K_o K_d Z_f(s)}, \quad (6)$$

$$G_0(s) = \frac{K_d K_0 Z_f(s)}{s}. \quad (7)$$

Figure 2 Block diagram of the DPLL in the frequency domain.

3. PHASE/FREQUENCY DETECTOR

The implemented PFD operates equally at low and high frequencies [Kodon,1995; Yuan,1989], which does not occur with the conventional PFD [Sayver,1990]. Figure 3 shows the circuit of the PFD which is composed of two blocks responsible for the generation of the Up and Down signals. Each block is composed of two pre-load branches and a transistor for the RESET of the block. Each block also has an output inverter and a transistor responsible for the PRESET.

Figure 3 PFD circuit.

The principle of operation of the PFD can be observed considering the generation of an Up signal, as indicated in Figure 4. When the reference signal is low, the pre-charge transistor M_{U1} conducts, and consequently sets the node (a) to high. Node (b) is also high due to the application of the PRESET signal (system initialization). When the reference signal makes a low-to-high transition, the transistor M_{U1} cuts, which puts node (a) in high impedance. This turns on the transistors M_{U6} and M_{U7} , forcing node (b) to low.

At the low-to-high transition of the VCO signal, the transistors M_{U2} and M_{U3} conduct and node (a) goes to low, and consequently the pre-charge transistor M_{U5} conducts. This situation forces node (b) to high. The signal Up is the inverse of the signal at the node (b). It can be observed from Figure 4 that the Up signal corresponds to the phase difference between the VCO and the reference signals.

Figure 4 Generation of Up pulse.

Figure 5 shows the HSPICE simulation of this circuit for input frequencies of 100MHz, 300MHz, 625MHz and 900MHz.

Figure 5 Generation of Up pulses by the PFD.

The charge pump circuit used, shown in Figure 6, is a current switch controlled by the PFD.

Figure 6 Charge pump circuit.

Figure 8 Control voltage of the reference circuit.

The VCO circuit shown in Figure 9 is composed of three stages of current mirrors. The circuit also has a differential amplifier at its output to square the signal generated by oscillator.

The current mirrors EC_1 , EC_3 and EC_5 has a 1:1 current transfer relation, while the current mirrors EC_2 , EC_4 and EC_6 has a 1:2 current transfer relation. The current relation of the mirrors EC_2 , EC_4 and EC_6 has been chosen in such a way that, during operation, they would drain half of the current generated by the transistors M_{V4} , M_{V9} and M_{V14} , respectively, but would drain the maximum current from the mirrors EC_1 , EC_3 and EC_5 .

Figure 9 VCO circuit.

When the transistor M_{V1} is conducting (low level at its gate), the current mirror EC_1 conducts, thus draining all the current generated by the transistor M_{V4} . Therefore, the current mirrors EC_2 and EC_3 are off. Since the current mirror EC_3 is off, the

current in the transistor M_{V10} (which is part of the current mirror EC_4) is half of the current produced by the transistor M_{V9} . The current in EC_4 (relation 1:2) and it turns on the current mirror EC_5 . The current produced by M_{V14} is drained by the current mirror EC_5 , and the current mirror EC_6 cuts off. Therefore, the signal at the gate of the transistor M_{V1} goes to high, and the oscillation starts.

The gain of the VCO set by $K_0 = (\Delta f / \Delta V)$ can be obtained using the VCO characteristic curve shown in Figure 10.

Figure 10 VCO characteristic curve.

5 LOOP FILTER

Figure 11 shows the passive second order loop filter designed.

Figure 11 DPLL second order loop filter.

It has been used a second order loop filter to reduce the ripple of the system, as it would occur if a first order loop filter had been used [Gardner,1980; Meyr,1990].

The impedance of the second order loop filter is given by:

$$Z_f(s) = \left(\frac{b-1}{b} \right) \frac{s\tau + 1}{sC \left(\frac{s\tau}{b} + 1 \right)} \quad (8)$$

where $b = (C/C_1) + 1$, $\tau = RC$.

The open loop transfer function of the charge pump DPLL using a second order loop filter is:

$$G_0(s) = K_0 \left(\frac{I_p}{2\pi} \right) R \left(\frac{b-1}{b} \right) \frac{s\tau + 1}{s^2 \tau \left(\frac{s\tau}{b} + 1 \right)}. \quad (9)$$

A method of design of DPLL loop filter is to adopt values of cut frequency and phase margin, and then the values of the filter elements can be determined [Keese,1996].

Using Equation (9), the value of the τ can be determined as a function of ω .

$$G_0(j\omega) \Big|_{s=j\omega} = K_0 \left(\frac{I_p}{2\pi} \right) R \left(\frac{b-1}{b} \right) \frac{j\omega\tau + 1}{-\omega^2 \tau \left(\frac{j\omega\tau}{b} + 1 \right)}. \quad (10)$$

The system phase margin, PM is:

$$PM = \arctag(\omega\tau) - \arctag\left(\frac{\omega\tau}{b}\right) + 180^\circ. \quad (11)$$

The cut frequency can be obtained by taking the derivative of the phase margin by ω and turning it equal to zero:

$$\frac{dMF}{d\omega} = \frac{\tau}{1+(\omega\tau)^2} - \frac{\left(\frac{\tau}{b}\right)}{1+\left(\frac{\omega\tau}{b}\right)^2} = 0, \quad (12)$$

$$\omega_c = \frac{\sqrt{b}}{\tau}.$$

H. Meyr and G. Ascheid [Meyr,1990] also deduced an expression to obtain an expression to the DPLL cut frequency as a function of the VCO gain K_O , the charge pump output current I_p , and the value of the DPLL filter resistance R , given as:

$$\omega_c = K_0 \frac{I_p}{2\pi} R \left(\frac{b-1}{b} \right). \quad (13)$$

The phase margin of a DPLL system having a second order filter can be adjusted by the proper selection of the value of b . Table 1, obtained using MATLAB, presents a variation phase margin as a function of b .

Table 1 - Variation of Phase Margin as Function of b.

b	6	8	10	12	14	16	18	20
PM(Degrees)	45	51	54	57	60	62	63,47	64,82

Therefore, the design of a loop filter may begin with an adequate value of phase margin, and then Equations (12) and (13) can be used to obtain the values of the filter components.

6. LAYOUT AND SIMULATIONS

The final layout of the DPLL circuit, implemented in ES2 0.7 μ m CMOS technology, is given in Figure 12. The final simulations, using HSPICE and considering the parasitic capacitances, are shown in Figure 13.

Figure 12 DPLL final Layout

...The DPLL open loop transfer function is given by:

$$G_0(s) = K_0 \left(\frac{I_p}{2\pi} \right) R \left(\frac{b-1}{b} \right) \frac{s\tau + 1}{s^2 \tau \left(\frac{s\tau}{b} + 1 \right)}. \quad (14)$$

where $K_0 = 127,8 \left(\frac{\text{MHz}}{\text{V}} \right)$, $I_p = 500(\mu\text{A})$, $b = 11$, $\tau = RC = 1,7 \cdot 10^{-8}$, $R = 3K4(\Omega)$

Then, the DPLL open loop transfer function (Equation 14) becomes:

$$G_0(s) = \frac{3,357s + 1,9751 \cdot 10^8}{2,6273 \cdot 10^{-17} s^3 + 1,70 \cdot 10^{-8} s^2}. \quad (15)$$

Figure 14 shows the Bode diagram of this transfer functions.

(b)

Figure 13 Simulations of control voltage and synchronized signals.

Figure 14 Bode diagram of the DPLL designed.

For the system the phase margin (PM) is:

$$PM = \arg[G_0(\omega_c)] + 180^\circ = 56,44^\circ$$

where ω_c is DPLL cut frequency.

Since the phase margin is positive, the DPLL is stable, according to the criteria of Nyquist.

7. CONCLUSIONS

This work presented the design of a DPLL that can be used as a clock recover circuit in systems operating at 622MHz under the SONET/SDH protocols. It has presented the design of each block of the DPLL.

The main feature of the DPLL is its short synchronization time, which was possible due to the use of an initialization circuit in the charge pump and a high gain loop and a loop filter with a short time-constant.

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BIOGRAPHY

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