NEW TECHNIQUE FOR THE IMPLEMENTATION OF DIGITAL DEMODULATION IN FIBER OPTIC GYROSCOPES

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Abstract. *This paper describes a new technique for the demodulation of Sagnac fiber optic gyroscopes, based on the zero-crossing technique. The technique uses a digital approach with a quasi-synchronous clock, which allows for the implementation of very high resolution and low cost gyroscope demodulation circuits. The proposed demodulation circuit was tested in laboratory, using a emulated gyroscope signal. The experimental results measured in the prototype showed that the final resolution of the detection scheme is 1000 times better than the resolution possible to achieve in the conventional synchronous clock zero-crossing digital demodulator.*

Keywords: *fiber optic gyroscopes, digital demodulation, zero-crossing demodulator*

1. INTRODUCTION

Fiber optic gyroscopes based on the Sagnac effect present a very high resolution when operated in closed loop (Culshaw, 2005), but this high resolution is achieved by employing very high cost components, and such systems cannot be used for low cost applications (Kersey et al, 1990, Toyama et al, 1992). Several techniques have been presented to obtain low cost demodulation schemes for Sagnac fiber optic gyroscopes, and the synchronous zero-crossing demodulation can be implemented with very simple circuits (McCain,1992, Rodrigues,1999). However, this simplicity is associated with a low resolution, which severely limits the application of gyroscopes constructed with such circuit technique.

If a higher resolution is needed in a synchronous demodulation circuit, it is necessary to use high cost and sophisticated very high frequency digital circuits. For example, if a resolution of 100 ps is required, the frequency of the digital clock (and the digital counters) has to be 20 GHz, which results in a very expensive implementation. The technique presented in this paper is based on the digital zero-crossing demodulation scheme, but it uses a quasi-synchronous clock to achieve very high resolution.

2. Zero-crossing demodulation technique

In a fiber optic gyroscope, the rotation rate information is obtained from the phase shift measured between two light beams traversing the loop in opposite directions. The detected light in the output of the fiber coil is converted to electric current by a photodetector, usually a fast response photodiode. The block diagram of a basic open loop Sagnac gyroscope is presented in Fig. 1.

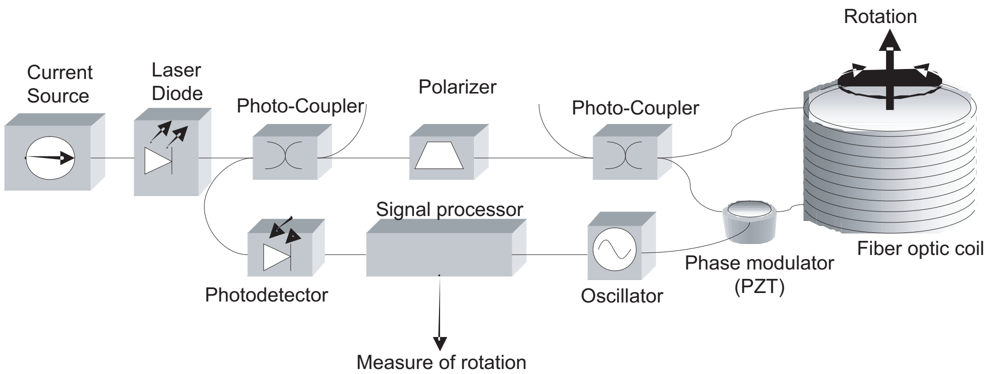

Figure 1. Block diagram of an open loop Sagnac fiber optic gyroscope

The phase modulator (PZT) is used to determine the sense of the coil's rotation, and also helps to reduce the $1/f$ noise in the transimpedance amplifier which is necessary to convert the current from the photodiode into voltage (Nascimento et al, 1999) .

The current intensity in the output of the photodiode can be written as:

$$I_{out} = \frac{I_0}{2}\left\{1 + cos\left[\Delta\phi_s + \phi_m cos\left(2\pi f_m t\right)\right]\right\} \tag{1}$$

where I_o is the peak amplitude of the detected light intensity, $\Delta\phi_s$ is the phase shift to be measured, ϕ_m is the modulation depth of the PZT, and f_m is the modulation frequency.

The output signal current in the photodiode obtained from from a sinusoidally modulated gyro with $\Delta\phi_s = 0$ and $\phi_m = 2.0$ is shown in Fig. 2(a). The result of passing this signal through a zero-crossing detector is shown in Fig. 2(b). It is important to notice that the value of ϕ_m depends on which technique will be used for the demodulation, as it has been shown recently (Ferreira et al, 2007) that the minimum detectable signal in a intensity noise limited fiber optic gyroscope depends strongly on the value of ϕ_m.

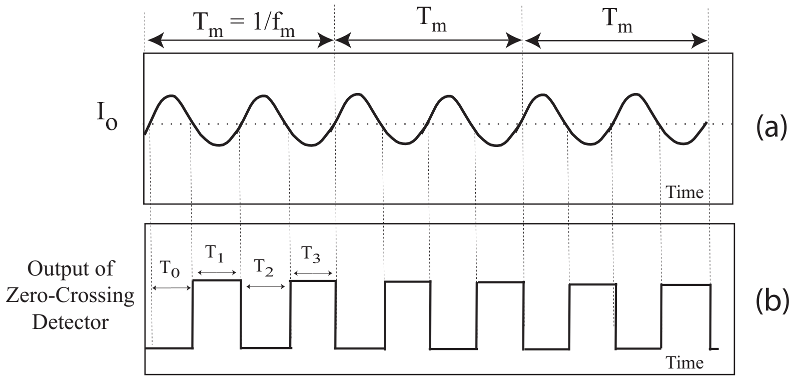

Figure 2. Current intensity in the photodiode (a); Voltage signal after zero-crossing detector (b)

The waveform obtained after the zero-crossing detector is periodical, with a period given by $T_m = 1/f_m$. The zero-crossing theory shows that it is possible to calculate $\Delta\phi_s$ (which is a function of the rotation) by measuring the time intervals of the negative cycles of the modulated signal (McCain,1992, Alves,1999)).

3. The proposed technique

Several techniques were proposed to measure $\Delta\phi_s$ using the zero-crossing theory, using analog circuits (Ferreira et al, 2007b, Tselikov et al, 1998) because the digital zero-crossing technique requires a prohibitive, extremely high clock frequency to obtain a high resolution gyroscope. An attempt of overcoming this weakness of the technique was presented by McCain (1992), with the introduction of a low frequency asynchronous clock. However, the DC and RMS errors presented in the measured values of $\Delta\phi_s$ with the asynchronous clock limited the application of the digital zero-crossing detection scheme, and the digital demodulation scheme was practically abandoned, except for low resolution systems.

In Fig. 3 it is shown the output current on the photodiode for $\Delta\phi_s = 0.4$ rad and $\phi_m = 2.0$. It can be easily noticed that the periods T_0 and T_2 are practically the same as seen when $\Delta\phi_s = 0$, but T_3 and T_2 changed. Since $\Delta\phi_s$, for small values, is approximately proportional to the difference of the time intervals $\Delta T = T_3 - T_1$, it is possible to calculate the desired phase shift $\Delta\phi_s$ simply by measuring these time intervals and calculating $T_3 - T_1$.

It is possible to prove that for any value of $\Delta\phi_s$ the following equation is valid:

$$\frac{\Delta\phi_s}{\phi_m} = cos(\frac{\omega_m T_0}{2})sin(\frac{\omega_m \Delta T}{4}) \tag{2}$$

The new technique proposed uses a quasi-synchronous clock, which frequency has to be adjusted to:

$$f_{ck} = k\frac{w}{Z}f_m \tag{3}$$

where k, W and Z are integers and the product kW cannot be a multiple integer of Z. This clock frequency will be synchronous to the modulation frequency f_m at every Z periods, as shown in Fig. 3, where a diagram showing the principle of operation of the technique is presented, for $Z = 3$, $W = 8$, $k = 2$ and $f_m = 100$ kHz.

In the proposed technique the system will count and accumulate the clock pulses during times interval T_1 (N_1 pulses) and T_2 (N_2 pulses), for Z periods. These time intervals (T_1, T_2) are obtained by dividing by two (with a flip-flop) the signal in the output of the zero-crossing detector.

The value of the difference between N_1 and N_2 is given by:

$$\Delta N = Z(N_2 - N_1) = (T_2 - T_1)f_m kW. \tag{4}$$

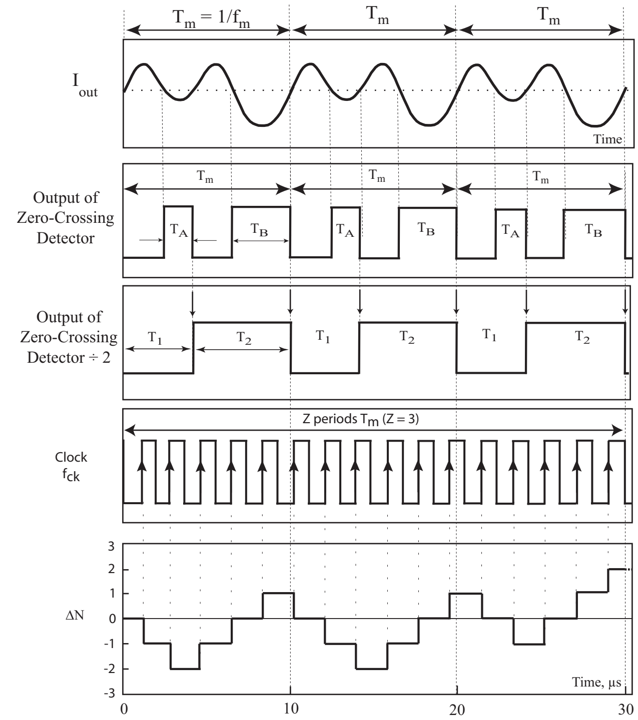

Figure 3. Principle of operation of the zero-crossing demodulation with quasi-synchronous clock

Due to the symmetrical structure of this scheme, only counts in multiples of two are obtained and, after Z periods, the minimum number of accumulated pulses which can be counted in a period of the modulation frequency $T_m = 1/f_m$ is $\Delta N = 2$, and the maximum resolution of the system can be written as:

$$\frac{T_2 - T_1}{T_m} = \frac{2}{kW}. \tag{5}$$

As the resolution of a conventional synchronous clock demodulator (McCain,1992) is only $2/k$, the resolution of the proposed system is increased W times by using the quasi-synchronous clock.

4. Circuit implementation

The technique was implemented using the circuit presented in Fig. 4.

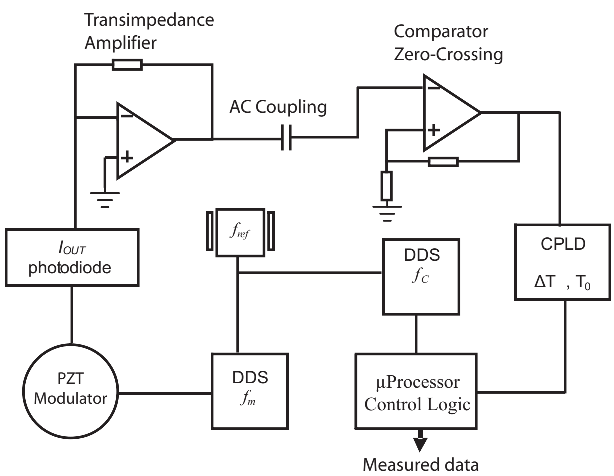

Figure 4. Block diagram of the circuit which implements the zero-crossing demodulation with quasi-synchronous clock

A transimpedance amplifier converts the current of the photodiode in voltage, a fast comparator detects the zero-crossing and a Complex Programming Logic Device is used to count the pulses during time intervals T_1, T_2 and calculate

ΔT. The frequencies f_m and f_{ck} are generated with two Digital Direct Synthesis (DDS) integrated circuits.

The use of a DDS to generate the frequencies f_m and f_{ck} is very convenient, because the relationship between these two frequencies, which must follow the law presented in EQ (3), can be controlled digitally, since the output signal of a DDS is an analog signal controlled by a digital word, as shown in Fig. 5, where a block diagram of a DDS is shown. The prototype was built using the DDS AD9851 from Analog Devices, which is capable of operating with frequencies up to 180 MHz. The CPLD employed in the digital demodulation was configured to present the internal structure shown in Fig. 6. The CPLD XC9572XL 5ns from Xilinx was used.

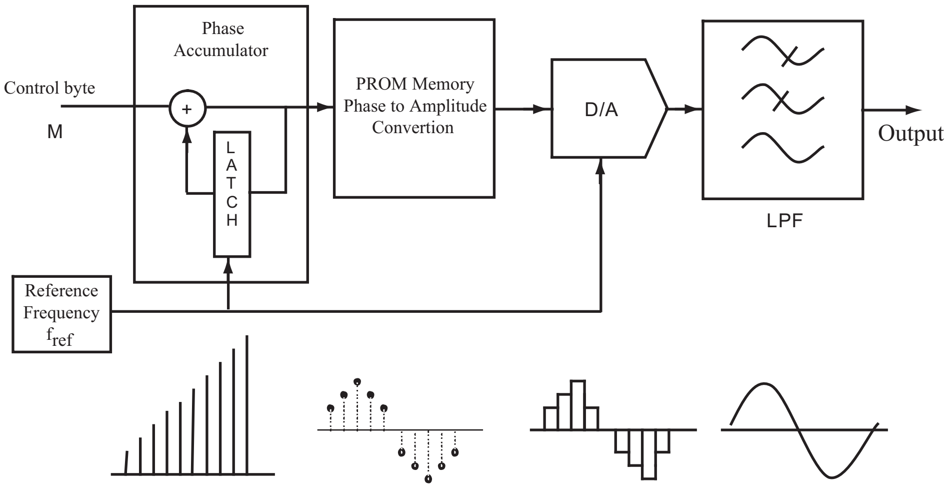

Figure 5. Block diagram of the DDS integrated circuit

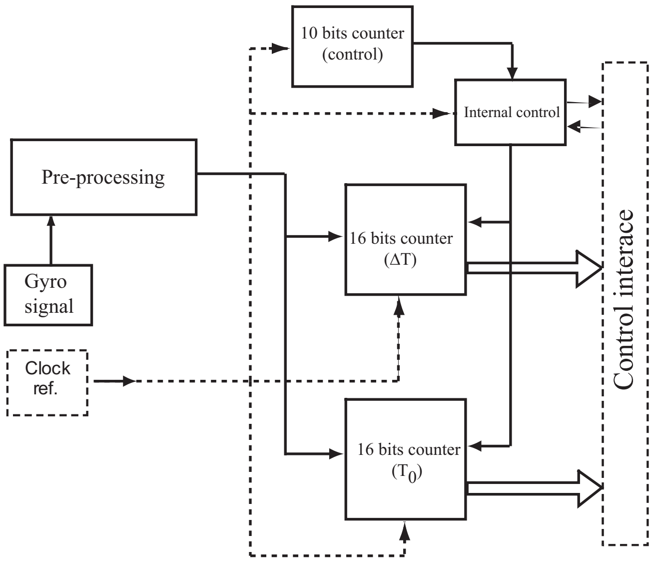

Figure 6. Diagram of the internal configuration of the CPLD XC9572XL 5ns to implement the proposed demodulator.

5. Experimental results

To test the technique, a special circuit which emulates the signal obtained after the zero-crossing comparator of a gyroscope submitted to a very small $\Delta\Phi_s$ was developed, using another CPLD.

The prototype was tested using three gyroscopes signals, which had an imposed ΔT of 50 ns, 100 ns and 150 ns. The gyroscope signal had a modulation frequency $f_m = 100$kHz and the system operated with a clock frequency of 10.01001 MHz. The values of $k = 100$, $W = 1000$ and $Z = 999$ were used, so that an improvement of 1000 should be obtained when the demodulator is compared with a conventional synchronous demodulator scheme. From this setup, it is expected that such a gyroscope demodulator system could be able to measure time intervals as low as 200 ps, which corresponds to a resolution of 20 ppm. The measured results are presented in Fig. 7, where each point plotted is actually the mean value of the last 50 samples acquired sequentially.

The experimental results show that the resolution obtained is within ± 20 ps, which is in agreement with the theory presented for this new zero-crossing technique. It is important to notice that the sampling frequency of the gyroscope has to be limited, due to the fact that Z periods of time are necessary to obtain a value of ΔT. However, with the presented configuration, it is possible to obtain 101 samples per second, a value considered sufficient for airborne gyroscope applications, as for example, in satellite launching vehicles (SLVs).

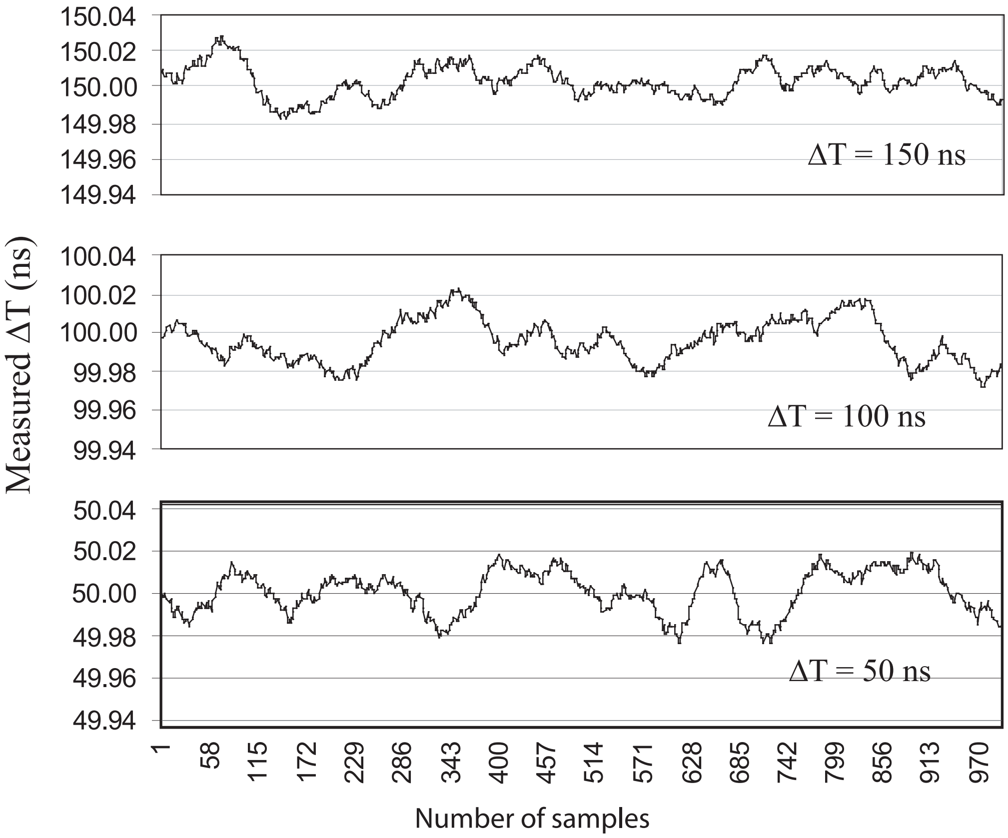

Figure 7. Measured results of ΔT, for gyroscopes signals with $\Delta T = 150$ ns, $\Delta T = 100$ ns, and $\Delta T = 50$ ns

It is also important to notice that the technique is not restricted to gyroscopes demodulation systems, but can be employed in any system which requires an accurate duty-cycle measurement, with high resolution. It is also very important to notice that by increasing the value of k, a higher resolution can be achieved. For example, if a higher clock frequency is allowed, in a system with $k = 1000$, $W = 1000$ and $Z = 999$, which results in a clock frequency f_m in the order of 100 MHz, it is possible to obtain a 2 ppm resolution.

It was demonstrated a new technique of digital demodulation of gyroscopes signals, which can be implemented with low cost signals and presents a high resolution, overcoming the well known problems faced by the synchronous and asynchronous digital zero-crossing demodulations schemes. The technique can be used to build gyroscopes with high resolution; a resolution of to 2 ppm can be achieved for a clock frequency of 100 MHz. Experimental results measured in a laboratory prototype confirmed that the systems performs much better that the conventional synchronous digital demodulator (with a resolution 1000 better) and do not present the DC and RMS errors found in the asynchronous digital demodulator.

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