A Simple Wide-Band Frequency Independent Quadrature Phase Shifter

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Abstract—**Quadrature Phase Sensitive Detectors (QPSD) are a very important part of phase measuring systems such as communication receivers. These types of devices are able to measure phase angles between two periodic signals very accurately even in the presence of noise. In the QPSD system, there is a specific block that produces a 90° phase shift for a sinusoidal input signal. Current design approaches are based on either a simple differentiator or integrator but they have some disadvantages such as frequency dependency. In this paper, the authors present a new design scheme for a simple, low cost Quadrature Phase Shifter (QPS). This new design scheme exploits the current controlled gain of operational transconductance amplifiers (OTA) which yields a relatively simple QPS design. The theoretical derivation and characterization of the new design scheme are provided. In addition, we present simulation and experimental results.**

I. INTRODUCTION

Frequency independent phase shifting has been a technical challenge for many years. In general, there are two approaches for producing a frequency independent phase shift: Analog and Digital. For the digital design, there are two choices: Hilbert transformer or microprocessor controlled passive or active RC network. The Hilbert transformer is a classic approach which is based on the Hilbert transform. Implementing this function needs a switched capacitor based circuit which is limited by a narrow bandwidth [1]. A microprocessor controlled system has a sophisticated structure that is very expensive [2]. In order to design low cost phase shifters, many analog design engineers developed several methods that are primarily based on the properties of analog multipliers or voltage controlled resistors [3]. While in many cases an ideal analog arbitrary phase shifter is desired, there are special cases designing wide band phase shifters with a specific constant phase shift is very important. The most important phase angles used in instrumentation systems are 90° and 180°. For producing two sinusoidal signals with 180° phase difference, over a wide frequency range, there is a very simple and low cost method [4,5]. In this paper, we present a simple and low cost method for generating a 90° phase shift. In this method, a specific property of Operational Transconductance Amplifiers (OTA) [6] is exploited to eliminate the frequency dependency of a simple differentiator. The design theory has been described and a low cost electronic circuit has been wired to show the validity of the theory.

II. THEORY

Fig.1 shows the overall block diagram of the proposed system. The fundamental part of this system is the differentiator. In this section, the 90° phase shift is produced but the output amplitude varies with frequency. The direct relationship between output amplitude and frequency is used to compensate the frequency effect. If one can design a specific gain controlled amplifier where its gain can be inversely controlled with an independent current or voltage, the goal is reached. So, the remaining procedure is to design a circuit to convert the frequency to voltage (or current). We can use a frequency-to-voltage converter but there is another approach. Since the output of the differentiator is an increasing function of the input frequency, one can use it to control the gain of the gain-controlled amplifier. By rectifying and filtering the output signal of the differentiator, a dc voltage will be obtained that is linearly related to the input frequency. This voltage will then be applied to the gain controlled amplifier in order to obtain a frequency independent amplitude at output. The above description can be shown in the following expressions. Let's assume

$$V_i = A.Sin(\omega.t) \qquad (1)$$

Then we will have:

$$V_1 = A.G_i.R_t.C_t.\omega.Cos(\omega.t) \qquad (2)$$

Assuming G_C and G_R as the gain values of the half-wave Rectifier/Filter and the voltage-to-frequency converter respectively, then we will have:

$$I_C = A.G_i.G_R.G_C R_t.C_t.\omega \qquad (3)$$

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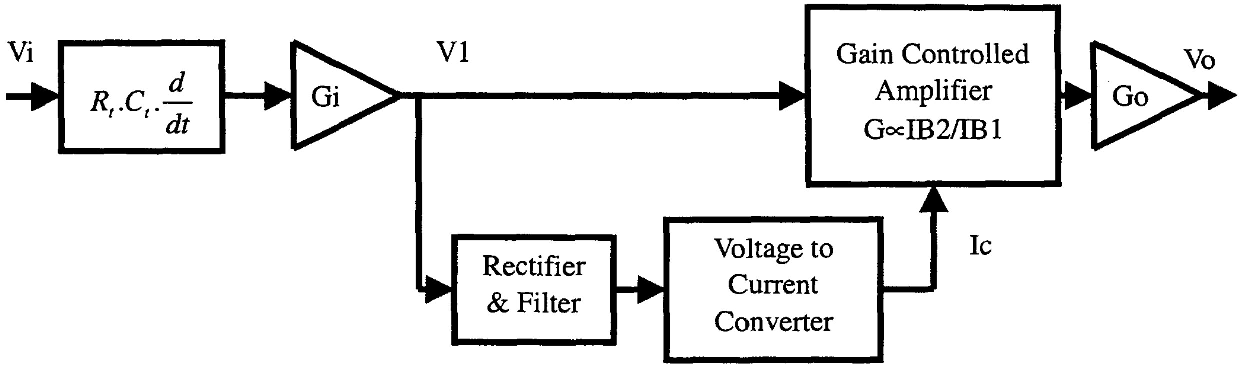

Fig 1: The Overall block diagram of the system

The gain-controlled amplifier must have a gain value that inversely depends to I_C so the gain relationship of the amplifier will be:

$$G = \frac{G_g}{I_C} \tag{4}$$

By using (2), (3) and (4) the output turns out to be:

$$V_O = \frac{G_g}{G_R.G_C}.Cos(\omega.t) \tag{5}$$

It can be inferred that the output does not depend only on frequency, but also on the input signal amplitude and even the time constant of the differentiator ($R_t.C_t$). In fact, this scheme is an automatic gain controlled circuit in addition to its frequency independent characteristic.

Now we have to design the gain controlled amplifier, but it is not a very complicated task because such an amplifier is already designed.

III. GAIN CONTROLLED AMPLIFIER

This kind of amplifier can be designed with two Operational Transconductance Amplifiers (OTA) [6]. The schematic diagram of the amplifier is shown in Fig.2. According to [6] the overall gain expression of this amplifier is:

$$V_O = \frac{R_O.I_{B2}.V_I}{I_{B1}.R_X} \qquad g_{m1}.R_X >> 1 \tag{6}$$

where g_{m1} is the transconductance of OTA1. This characteristic satisfies our need because it is inversely related to I_{B1}. Moreover, the bandwidth of the OTA's is directly related to the gain controlling current. The gain controlling current is directly related to the output signal amplitude of the differentiator and this value is in turn related to the input frequency. Therefore, the bandwidth of OTA will be increased by increasing the input frequency! This is an amazing characteristic of the scheme that can be achieved only by choosing a differentiator as a quadrature phase shifter. If an integrator had been chosen the relationship would has been reversed.

IV. EXPERIMENTAL RESULTS

The proposed system is implemented by off-the-shelf commercial components. The CA3280 operational transconductance amplifier is used to design the gain controlled amplifier. The OP27 operational amplifiers are used the differentiator and rectifier/filter. The amplifiers G_o and G_i must be phase-compensated amplifiers [7] because they must not contribute any phase error to the system. So, the TL074 quadrant op-amp is used for implementing phase-compensated amplifiers. The component values has been selected so that the circuit parameters would be:

$R_X = 10K\Omega$, $C_X = 100nF$, $G_i = 100$, $G_O = 46.4$,

$R_o = 100\Omega$, $G_C = \frac{1}{\pi}$, $G_R = \frac{1}{1000}$ $[A/V]$,

$I_{B2} = 0.6$ $[mA]$,

After wiring all of the components on a breadboard, the magnitude and phase of the output signal and the output of the differentiator are measured by a precision lock-in amplifier (Stanford Research Systems SR-830).

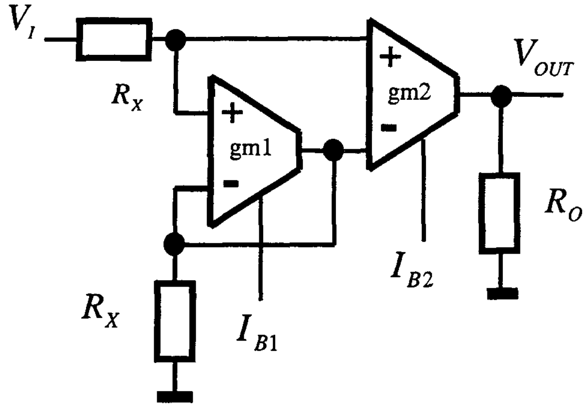

Fig. 2: Gain controlled amplifier [6].

The variations of the output amplitudes and phases in term of frequency are shown in Fig.3 and Fig.4 respectively. It is shown in Fig.3 that the output phase remains constant in three frequency decades. Though, a small deviation from -90° does exist. This small deviation is due to stray capacitors between connections, pins and wires on the breadboard. Since the main purpose of this circuit is only to show the general characteristic of such system so, no more efforts were done to eliminate the effects of stray capacitors. As a matter of fact, the authors want to show a rough agreement between the theory and experimental results.

In Fig.4, the solid line shows the output amplitude variations vs. frequency and the dashed line shows the output amplitude variation of differentiator vs. frequency. From Fig.3, it can be determined that for frequencies between 500Hz to 10kHz (almost one and half decades) the frequency independency does exist but for the frequencies below 500Hz and above 10kHz this feature degrades. For the frequencies above 10kHz, the differentiator deviates from its ideal characteristic and this phenomenon affects the performance of the overall system. So, by designing a better differentiator one can increases the bandwidth. The main degradation actually occurs in low frequencies.

According to Fig.4, for frequencies lower than 200Hz the output amplitude has a linear relationship with frequency that indicates the gain controlled amplifier has no effect. In the low frequencies, the output amplitude of the differentiator is very low so, it becomes comparable to the dc offset voltages of exploiting op-amps. In order to investigate the effect of offset voltages, one can consider that all of them produce a dc offset current I_{OFF} in addition to I_C. Therefore, the gain relationship of the gain-controlled amplifier will be:

$$G = \frac{G_g}{I_C + I_{OFF}} \qquad (7)$$

By using (2), (3) and (7) the output turns out to be:

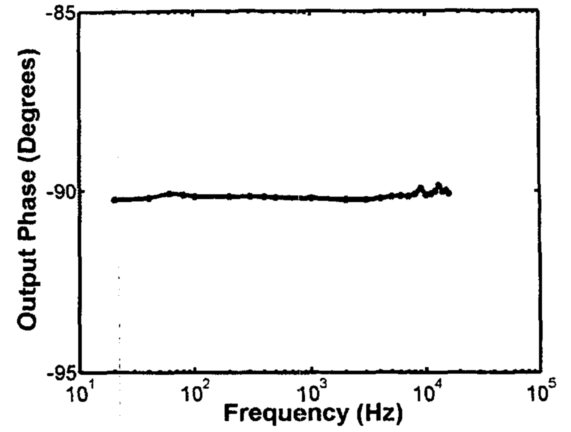

Fig. 3: Output phase vs. frequency.

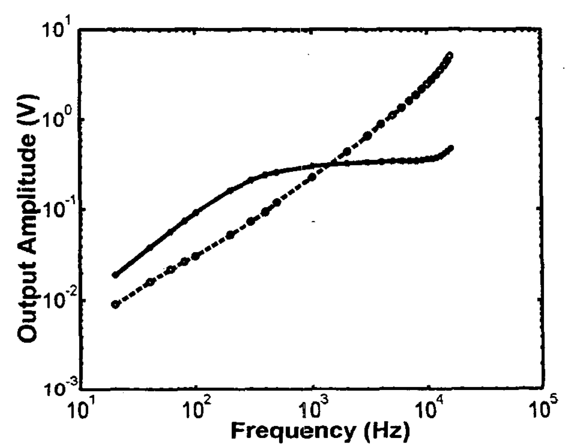

Fig. 4: Dashed line is the output amplitude variation of the differentiator and solid line is the output amplitude variation of the scheme.

$$V_O = \frac{A.R_t.C_t.G_i.G_g.\omega}{A.G_i.G_R.G_C R_t.C_t.\omega + I_{OFF}}.Cos(\omega.t) \qquad (8)$$

According to (8) it is obvious that for the low frequencies the first term in the denominator is much lower than I_{OFF} so the amplitude of the output will be linearly dependent on the frequency. By increasing the frequency, the first term in the denominator will be increased and for the frequencies higher than 500Hz, I_{OFF} can be ignored in comparison to the first term, then the output relationship will be independent of frequency. So, in order to design a wide-band frequency independent QPS this effect must be eliminated (or at least decreased to an acceptable level). This job is almost impossible by using commercial discrete circuits so in order achieve an offset free system we have to integrate the circuit. By integration, one can design a simple transistor level circuit that inherently has a wider frequency response and lower offset values.

V. CONCLUSIONS

In this paper, a simple frequency independent quadrature phase shifter has been introduced. However, the theoretical calculation shows that there is no relationship between the amplitude of the output signal and the frequency, the experimental results indicate that for low frequencies there is a deviation from the theoretical results. This degradation is caused by non-zero offset voltages of the exploited operational amplifiers. But the experimental results have a very good agreement with the theory. Future efforts will focus on eliminating this degradation by using the transistor level integration. Designing quadrature phase sensitive detectors without any component exchanging mechanism, in order to achieve wider bandwidth, will be possible, by using this scheme.

VI. ACKNOWLEDGMENT

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