A Simple Low Cost Frequency-Independent Phase Shifter

By

Munir A. Al-Absi

EE Department, KFUPM
mkulaib@kfupm.edu.sa

في هذه الورقة نقدم تصميم جديد وسهل وقليل التكلفه لدائرة ازاحة زاوية الاشارة لاتتاثر بتغير ذبذبة الاشارة. التصميم بني باستخدام دوائر متكاملة رخيصة ومتوفرة . يمكن تغيير الازاحة باستخدام مقاومه تتغير اليا والتعويض عن الزياده او النقص في ذبذبة الاشارة باستخدام مكثف يتغير اليا. لقد تم التأكد من عمل وكفاءة النظام بالتجربة المخبرية والمحاكاة باستخدام برنامج PSPICE .

Address for correspondence:

Dr. Munir A. Al-Absi
Electrical Engineering Dept, KFUPM
Dhahran, Saudi Arabia
1139

E-Mail: mkulaib@kfupm.edu.sa

A Simple Low Cost Frequency-Independent Phase Shifter

By

Munir A. Al-Absi

EE Department, KFUPM
mkulaib@kfupm.edu.sa

Abstract: A new, simple and low cost frequency independent phase shifter is presented. The design is based on a simple op-amp phase shifter with programmable floating resistor and programmable capacitor. The phase shift can be varied using the programmable resistor. Compensation for the variation in the frequency is achieved using the programmable capacitor. Experimental and simulation results confirm the functionality of the proposed scheme.

Key words: phase shifter, C-multiplier .

1 INTRODUCTION

Phase shifters are widely used in many areas of electronics instrumentation. This includes instrumentation, signal processing, communication and control [1]-[6]. In testing and measurements systems two sinusoidal signals having between them an adjustable, precise phase difference that is insensitive to frequency is required. Phase shifters are also used in many high frequency applications as indicated in reference [7] and the references cited therein. A frequency-independent phase shifter that can provide a precise phase shift varying from 0 to 360 was developed in [8]. In this approach, a bank of capacitors, a microcontroller, two sine-to-square wave converters, phase sequence detector, integrator, summer and a voltage controlled resistor are used. This of course will add up to the cost and size of the shifter. A programmable phase shifter was reported in [9] and the circuit is shown in figure 1. Programmability is achieved using an operational transconducatnce amplifier (OTA) based programmable resistor. This approach is suitable for single frequency application. If the frequency of the input signal is varying then there should be a way to compensate for the frequency variation. In this work, the circuit of figure 1 is modified to provide a frequency-independent phase shifter. The phase shift can be varied from 5º to 160º over the frequency range from 100Hz to 10kHz. The approach can be adapted for larger span in the phase shift and higher frequency range. In section 2, block and circuit diagram of the proposed system is presented. Experimental and simulation results are presented in section 3. Section 4 concludes the paper.

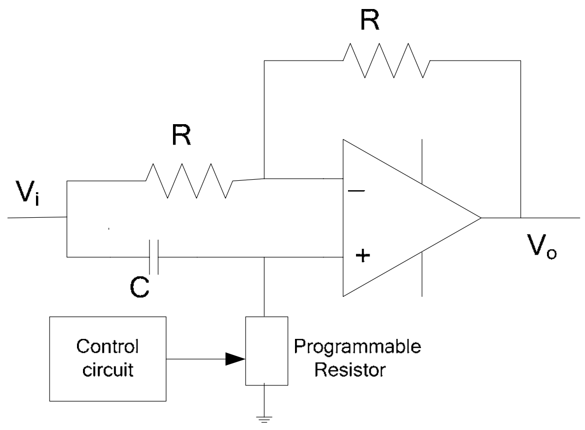


Figure1. *Programmable phase shifter*

2 PROPOSED SYSTEM

The complete block diagram of proposed system is shown in figure 2 and it consists of a programmable resistor R_e and a programmable capacitor C_e , a frequency-to-voltage converter with voltage scaling circuit. The programmable resistor, R_e and the programmable capacitor, C_e are implemented using OTAs approach presented in [10] and [11].

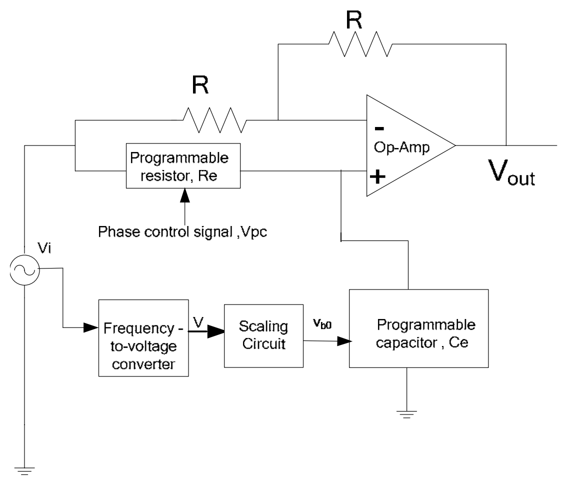


Figure.2. *Proposed frequency-independent phase shifter*

With reference to figure 2, resistor R_e is used to control the phase via the control circuit where the programmable capacitor C_e is used to compensate for the variation in frequency. The frequency-to-voltage converter is mainly used to compensate for the change in frequency by changing of the value of the capacitor C_e.

If the frequency changes, the frequency-to -voltage converter output, V, will change and scaled by the scaling circuit to produce a voltage V_{b0}. The voltage V_{b0} is used to control the bias current of the OTA which in turn will adjust the value of C_e to compensate for the frequency variation.

Grounded C-multiplier

The circuit diagram of the grounded C-multiplier developed in [10] is shown in figure 3, and the value of C_e is given by:

$$C_e = C\frac{g_{m1}}{g_{m0}} \qquad (1)$$

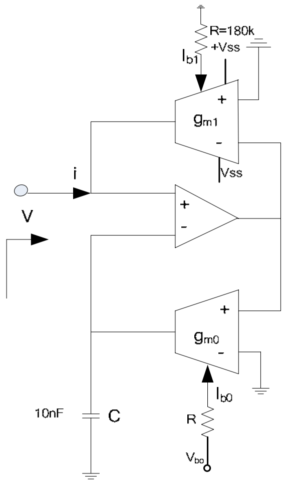


Figure.3. *C-multiplier*

where g_{m1} and g_{m0} are the transconducatne of the OTAs that depends on the bias currents I_{b1} and I_{b0} respectively.

Floating resistor

A floating programmable active resistor using OTAs was developed in [11] is given in figure 4. The equivalent resistance seen between V_1 and V_2 is given by:

$$R_e = \frac{1}{g_m} \qquad (2)$$

where g_m depends on the bias current of the OTA's and is given by:

$g_m = \frac{I_b}{2Vt}$ for OTA designed using bipolar transistors technology and Vt is the thermal voltage ≅ 26mv at room temperature.

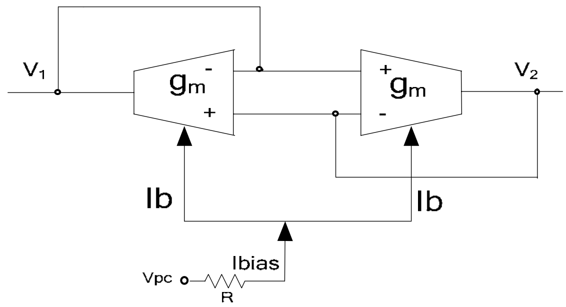


Figure.4. A floating p*rogrammable resistance*

With reference to figure 4, $I_b = \frac{Ibias}{2}$ and $g_m = \frac{I_{bias}}{4Vt}$. The phase control signal, Vpc is used to vary the bias current I_{bias} which in turn will vary the value of the floating programmable resistor.

With reference to figure 2, it is easy to show that the phase shift between the input and the output is given by:

$$\Phi = -2\tan^{-1}\omega C_e R_e \qquad (3)$$

Combining equations (1), (2) & (3) yields,

$$\Phi = -2\tan^{-1}\frac{2\pi C}{g_m}\frac{f g_{m1}}{g_{m0}} \qquad (4)$$

With $\frac{g_{m1}}{g_{m0}} = \frac{I_{b1}}{I_{b0}}$ equation (4) can be rewritten as,

$$\Phi = -2\tan^{-1} 8\pi Vt \frac{C}{Ibais} f \frac{I_{b1}}{I_{b0}} \qquad (5)$$

If the frequency varies, the frequency to voltage converter output voltage will change and hence adjust the value of C_e to compensate for the change in frequency so that the product $f\frac{I_{b1}}{I_{b0}}$ remains constant.

Frequency -to-voltage converter

The TC9400 frequency to voltage converter, F/V, is used. From the data sheet, the circuit can work for frequency range from DC-100kHz with maximum nonlinearity deviation of .05%. The circuit was tested experimentally with ±12 V over the frequency range 100Hz-10kHz. Experimental result for the F/V circuit is shown in figure5. It is evident from the plot that the relation between signal frequency and output voltage is linear and can be written as $V = kf$ +c, where k and c can be extracted from the plot.

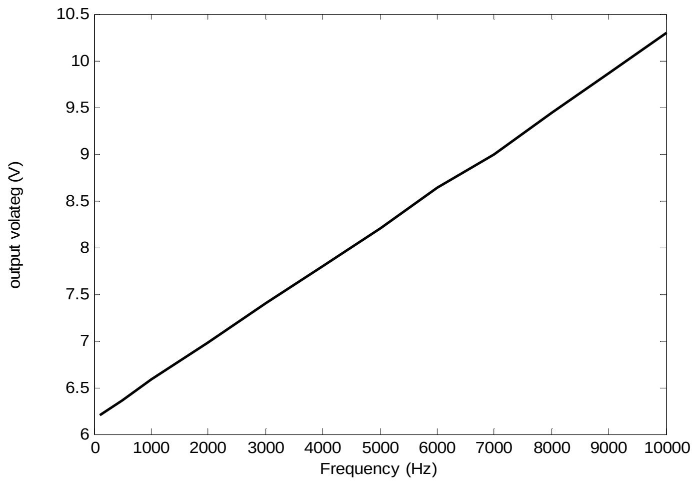


Figure 5. Output voltage VS frequency for the f /V converter

The scaling circuit is built around Op-Amp as shown in figure 6.

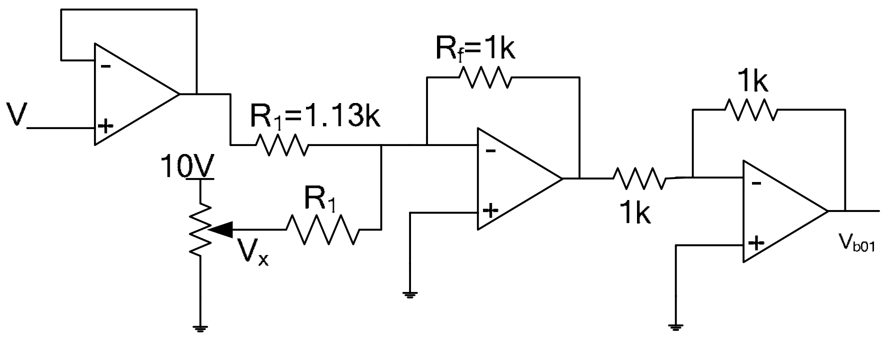


Figure. 6. Voltage scaling circuit

From figure 6, it can be shown that $V_{b0} = \frac{R_f}{R_1}(V + Vx)$

From figure 3, the bias current I_{b1} is given by:

$$I_{b1} = \frac{0 - 2*.7 - Vs}{R} \tag{6}$$

where Vs is the OTA supply voltage which is -5V

$$I_{b1} = \frac{3.6}{R} \tag{7}$$

The bias current I_{b1} is kept constant and can be adjusted if needed by varying R but should be kept within the OTA bias current range.

The current I_{b0} will be used to compensate for the variation in frequency as follows:

$$I_{b0} = \frac{V_{b0} - 2*0.7 - Vs}{R} = \frac{V_{b0} + 3.6}{R} = \frac{R_f}{R_1 R}(V + Vx) + \frac{3.6}{R} = \frac{R_f}{R_1 R}(kf + c + Vx) + \frac{3.6}{R}$$

$$I_{b0} = k\frac{R_f}{R_1 R} f + c\frac{R_f}{R_1 R} + Vx\frac{R_f}{R_1 R} + \frac{3.6}{R} \tag{8}$$

With V_x negative, R is selected based on the required bias current I_{b0} and by proper selection of V_x, the term $c\frac{R_f}{R_1 R} + Vx\frac{R_f}{R_1 R} + \frac{3.6}{R}$ can be made equal to zero, and equation (8) becomes,

$$I_{bo} = k\frac{R_f}{R_1 R} f \tag{9}$$

From equation 9, it is clear that the bias current I_{b0} is proportional to the frequency. Combining equations (5), (7), and (9) the phase shift can be expressed as:

$$\Phi = -2\tan^{-1} 8\pi Vt \frac{C}{Ibias}\frac{3.6R_1}{R_f k} \tag{10}$$

It is clear from equation (10) that the phase shift Φ can be varied using the bias current $Ibias$ irrespective of the frequency and hence a frequency-independent phase shifter can be developed.

Sensitivity analysis

Sensitivity analysis of the shifter with respect to passive components was carried out using equation (11) for C, R_1 and R_f in equation 10 and the results are shown in Table 1.

$$S_X^{\Phi} = \frac{d\Phi / dX}{\Phi / X} \tag{11}$$

In equation (11) X many be any variable for example C, R_1 and R_f.

In Table 1 A, B and D represent the rest of $\tan^{-1}$ argument in equation 10. Using Table 1 sensitivity was calculated for two extreme values of the phase shift e.g Φ= 5° and Φ=160° and values of S_C^{Φ} was found to be -0.0174 and -2.138E^{-3}. Similar calculation was performed for R_1 and R_f. The results are the same as for the capacitor C. This means that the proposed circuit enjoys very low sensitivities against variation in the passive components.

Component	Sensitivity equation
Capacitor C	$-\dfrac{CA}{\left(1+C^2A^2\right)\left(\tan^{-1} CA\right)}$
Resistor R_1	$-\dfrac{R_1B}{\left(1+R_1{}^2B^2\right)\left(\tan^{-1} R_1B\right)}$
Resistor R_f	$\dfrac{D/R_f}{\left(1+\dfrac{D^2}{R_f{}^2}\right)\left(\tan^{-1} D/R_f\right)}$

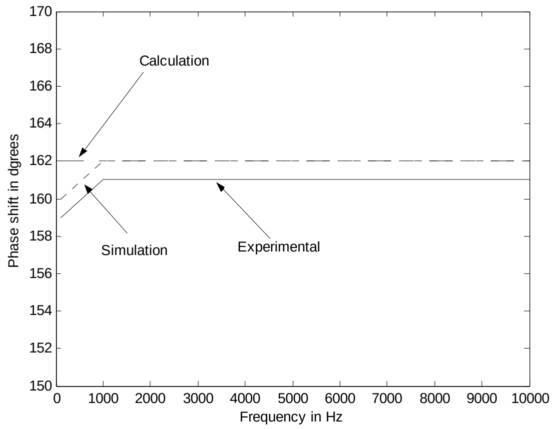
Table1. Sensitivity analysis

3 EXPERIMENTAL AND SIMULATION RESULTS

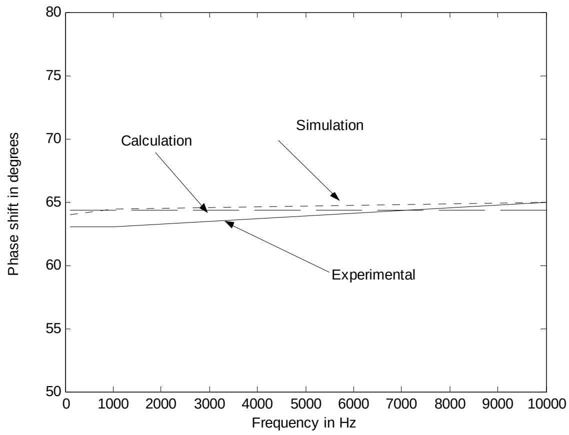
The proposed system was verified using both simulation and experimental testing. The results are tabulated in table 2. It can be seen from the table that phase can be varied from 5º to 160 º for a frequency range from 100 Hz to 10 kHz. The maximum phase error is around 3º compared to 7.2° in reference [6] and 7° in reference [7]. Plot for calculated, simulated and experimental phase shift for 100Hz, 1kHz and 10kHz are shown in figures 7a, b, c respectively. It is important to point out that, in the simulation effect of temperature was taken into account and the system performance is acceptable in the temperature range -20 to 70 Cº with a maximum error of 2% over dynamic range of 80mV. Finally, the system was simulated for noise analysis and the total output noise voltage is 3.092e-15 $\sqrt{V/Hz}$ for an input noise of 5.561E-8 and transfer function of unity.

	Phase shift calculated at 1Khz	Phase shift Simulation results $I_{b1} = 20\ \mu A$			Phase shift Experimental results $I_{b1} = 20\ \mu A$		
$I_{bias,}\ \mu_A$	Phase Φ	f =100 Hz	f = 1KHZ	f = 10 KHz	f = 100 Hz	f = 1KHz	f= 10KHz
140	5.1	5.2	5.4	5.4	4.8	5.4	5.6
100	7.2	7.7	7.8	8	7	7.5	7.9
40	17.9	18	18	18.4	17	18.5	18.3
10	64.3	64	64.4	65	63	63	65
6.2	90.8	92	91.8	91.8	89	91	91
3	129	130	127.8	127.8	128	129	129
1	162	160	162	162	159	161	161

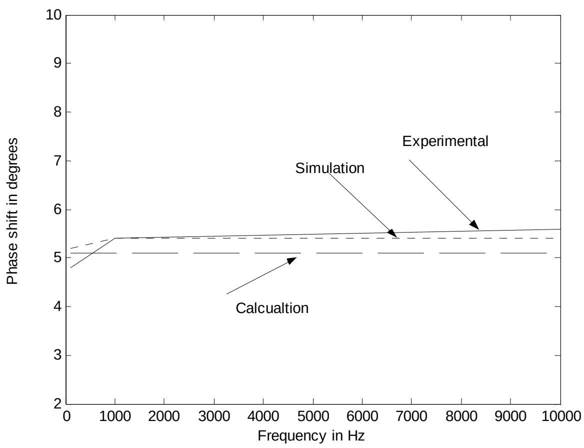
Table2. *Calculation, simulation and experimental results*



(a) I_{bias} =1μA



(b) I_{bias} =10 μA



(c) I_{bias} =140u

Figure.7. Plots of phase shifts vs frequency for different bias current I_{bias}

4 CONCLUSION

A simple low-cost frequency-independent phase shifter is developed. The new design eliminates the use of microcontroller, RC all pass filter, capacitor bank and phase detection circuit in addition to some others Op-Amp based circuits. Thus leading to low-cost and smaller design compared with that reported in reference [8] but less accuracy. The phase shift can be varied from 5 to 160 º over the frequency range 100 Hz to 10 kHz and dynamic range of 80mv with maximum error of 3°. The presented phase shifter is almost insensitive to passive components tolerance and noise. The maximum error in the phase shift is around 3º which is acceptable compared to existing approaches. The proposed scheme was verified experimentally and by simulation. The design can be adapted for higher frequency range and larger span in the phase shift.

ACKNOWLEDGMENTS

The author would like to thank Professor Abuelma'atti for his valuable comments and KFUPM for the support of this research.

REFERENCES

[1] M. Mittal and S. S Jamuar, "Programmable Frequency Independent Switched Capacitor Phase Shifter of Unity Gain", Measurement Science and Technology, Vol.2, 1991, pp.457-477.

[2] A. Helfric, "Phase Shifter Using Digital Techniques", EDN Vol.32, November 12, 1987, pp.289-290.

[3] B.K Jones, B.K Sharma and D.H.Bidle, "A Frequency-independent Phase Shifter", Journal of Physics E: Scientific Instruments, Vol.13, 1980, pp.1346-1347.

[4] B. Caowan, "A Versatile Phase Shifter for NMR Experiments and Other Applications", Measurement Science and Technology, Vol.13, 1992, pp. 296-298.

[5] M. Madihian, K,. Watanabe and T. Yamamoto, "A Frequency –independent Phase Shifter", Journal of Physics E: Scientific Instruments, Vol.12, 1979, pp.1031-1032.

[6] Doo-Hee Jung and In-Joong Ha, "Low-Cost Sensorless Control of Brushless DC Motors Using A Frequency-Independent Phase Shifter", IEEE Transactions On Power Electronics, Vol. 15, No. 4, July 2000, pp. 744-752.

[7] Miyaguchi K, Hieda M, Tarui Y, Hatamoto M, Kanaya K, Iyama Y, Takagi T, Ishida O, " A C-Ku band 5-bit MMIC Phase Shifter Using Optimized Reflective Series/Parallel LC Circuits", IEICE Transaction on Electronics, Vol. E86C (12): 2429-2436 DEC 2003.

[8] K. Sudhakar Rao, V. Jagadeesh Kumar and P. Sankaran, " Precision Frequency-independent Variable-Phase Shifter", Electronics Letters, February 1995, Vol. **31** No 3., pp 154-155.

[9] Muhammad T. Abuelma'atti and Uthman Baroudi, " A Programmable Phase Shifter for Sinusoidal Signals", Active and Passive Elec. Comp, 1998, Vol. **21**, pp.107-112.

[10] M.T Ahmed, I.A. Khan and N. Minhaj, " Novel Electronically Tunable C-multiplier" , Electronics Letters, January 1995, Vol. 31, No. 1, pp 9-10.

[11] Randall L. Geiger and Edgar Sanchez-Sinencio, "Active Filter Design Using Operational Transconductance Amplifiers: A Tutorial", IEEE Circuits and Devices Magazine, Vol. **1**, 1985, pp. 20-32.