AUTOMATIC FREQUENCY CONTROL TECHNIQUES FOR MICROWAVE ACTIVE FILTERS

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Abstract

The paper discusses Phase Locked Loop (PLL) and Magnitude Locked Loop (MLL) techniques based on Voltage Controlled Filter (VCF), for the Automatic Frequency Control (AFC) of active filters. Applications to a microwave planar filter are considered. Theoretical analysis, simulated and measured results are presented for both phase and magnitude control circuits enabling the filter to accurately track a reference signal.

Introduction

Characteristics of analog filters are vulnerable to fabrication tolerances, temperature drift and aging. AFC using the popular master-slave approach is the most feasible solution to control these characteristics [1]. This problem has been solved for a microwave filter in [2,3] by using typical PLL based on a Voltage Controlled Oscillator (VCO) matched to the slaved filter.

In contrast to the VCO based PLL, we propose in this paper for filters designers, a VCF based PLL (Figure 1.a) and a VCF based MLL (Figure 1.b) in order to simplify the frequency control circuitry. These two techniques are implemented in planar hybrid technology on duroid substrate. They are applied to control the central frequency of a microwave band-pass VCF tunable over the range (3.8-4.9 GHz). Measurements show that the filter central frequency tracks accurately a reference signal.

Theoretical principle

The theoretical principle of the two techniques is pointed out by considering the particular case of an ideal second order biquadratic band-pass VCF, with the following transfer function $\mathbf{H}(\mathbf{j}\omega)$:

$$\mathbf{H}(\mathbf{j}\omega) = \frac{\mathbf{j}\dfrac{\omega}{\omega_0 \mathbf{Q}_0}}{1 + \mathbf{j}\dfrac{\omega}{\omega_0 \mathbf{Q}_0} - \dfrac{\omega^2}{\omega_0^2}},$$

with $\mathbf{Q}_0 = \dfrac{\omega_0}{\Delta\omega_0}$ and $\Delta\omega_0$ rd/sec : bandwidth at -3 dB

The voltage controlled central frequency expression is : $\omega_0 = \mathbf{K}_c \mathbf{V}_c$, where :

$\mathbf{K}_c$: VCF conversion factor in rd/sec per volt.

$\mathbf{V}_c$: Voltage control in volt.

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Control based on PLL using a VCF :

This type of control circuit has been achieved at low frequencies [1]. It is based on the reduction of the phase difference between a reference signal and the one processed by the master VCF, at $\mathbf{f_{ref}}$ (reference signal frequency). For an ideal biquad filter, at ω_0 the phase shift of the band-pass filter is 0 degrees.

In the AFC circuit (Figure 1.a), the master filter is phase locked to the reference signal. The phase of the reference signal is compared with the phase response of the biquad filter by a phase comparator. The phase error is filtered out by the low pass filter, then amplified and fed back to adjust the central frequency ω_0 of the filter. The loop is locked when the phase of the band-pass filter output signal is equal to the phase of the reference signal. As a result, ω_0 is equal to ω_{ref}.

The analysis of the scheme (Figure 1.a) in the biquad filter case, based on control system theory, lead to the relation :

$$\omega_0 = \frac{\mathbf{K_c K_d} \alpha \mathbf{F}}{1 + \mathbf{K_c K_d} \alpha \mathbf{F}} \omega_{ref} \qquad (1)$$

with : $\alpha = \frac{2}{\Delta\omega_0}$ sec, $\mathbf{K_d}$: phase detector gain factor,
$\mathbf{F}$: DC gain of the amplifier.

We can notice from (1), that the steady-state filter central frequency ω_0 limit, for a constant reference signal frequency is : $\omega_0 \rightarrow \omega_{ref}$ if $\mathbf{K_c K_d} \alpha \mathbf{F} \rightarrow \infty$.

This proves that the frequency of the reference signal controls the central frequency of the filter.

Control based on MLL using a VCF :

In this case the control circuit minimizes the magnitude difference between a reference signal and the one filtered by the VCF, at $\mathbf{f_{ref}}$. For the same biquadratic filter previously defined, at the resonance frequency the peak gain is equal to 1.

In the AFC circuit scheme of Figure 1.b, the amplitude of the reference signal is compared with this of the output VCF signal. The magnitude error is amplified and turned back to control ω_0 the filter central frequency. The loop is magnitude-locked when the two compared amplitudes are equal, resulting in $\omega_0 = \omega_{ref}$.

The theoretical study of the scheme in Figure 1.b proves that the steady-state filter central frequency is :

$$\omega_0 = \frac{1 + 2\gamma\omega_{ref} + \sqrt{1 + 4\gamma\omega_{ref}}}{2\gamma} \qquad (2)$$

with : $\gamma = K_c K_d \alpha F$ sec, K_d : magnitude comparator gain factor.

If $\gamma \to \infty$ then $\omega_0 \to \omega_{ref}$. In the same manner, we can say that the frequency of the external signal commands the central frequency of the filter.

Application of these AFCs for microwave filters

Microwave filter design

Figure 2 shows the topology of the microwave band-pass planar filter. It is a distributed half-wave hybrid resonant structure. A varactor diode used as Voltage Controlled Capacitor (VCC) is placed in the middle of the resonator to make its central frequency electronically tunable.

The filter is implemented on duroid substrate (having a thickness of 0.5mm and a dielectric constant of 2.43) and is frequency tunable over the range (3.8-4.9 GHz). The VCC is a MACOM beam lead constant gamma gallium arsenide tuning varactor (MA46580).

Microwave filter AFCs design and simulation

To apply the two control techniques with this microwave planar filter, a two-way power coupler is used for dividing the reference power source between the reference branch and the filtered one. A phase comparator is needed for the PLL based control and a magnitude comparator for the MLL based control.

- Wilkinson power divider : A two-way wilkinson circuit [4] is choosen as a power divider in the two control systems. The Wilkinson is fabricated [5] on duroid substrate, well matched at all ports, presents a good isolation between output ports over the frequency range (3-5 GHz).

- Phase detector and magnitude detector : To accomplish the phase detection function, a microwave double balanced mixer is used. The magnitude detector is built with zero bias Schottky diodes. All RF elements are implemented on duroid substrate.

The PLL and the MLL techniques have the final functional scheme presented in Figure 3. A DC amplifier is used to amplify the comparison error of the loop.

The steady-state responses of the devices presented in Figure 3 are simulated with electrical models of lines, varactors and RF elements.

Figure 4 shows the tracking performance of the filter central frequency to the external signal frequency. Simulation results show that the PLL based control system has a precision varying from 0 to 1.3 % over the frequency range (4-4.6 GHz). Whereas the MLL based control offers a precision varying from 0.5 to 3.4% over the frequency range (4-4.6 GHz).

Microwave filter AFCs measurements

Figure 5 shows the measured response of the microwave planar tunable filter. It exhibits a minimum insertion loss of less than 2.8 dB, a -3 dB bandwidth of 0.38 GHz and a rejection greater than 12 dB. It is tunable over the frequency range (3.8-4.9 Ghz).

Figure 6 shows the tracking performance of the control techniques. The transmission response of the slaved filter is measured for several external reference frequencies and for each control method. The PLL based AFC enables the filter central frequency to track the external signal frequency with a precision varying from 0 to 0.19% over a frequency tuning range of (4.0-4.6 GHz). Finally the MLL based AFC offers a tracking precision of (0.5-3.6%) over a frequency tuning range of (4.0-4.6 GHz).

Comparison of AFCs

The PLL based technique is more precise than the MLL technique. This is due to the fact that the losses of the microwave filter at the central frequency are not constant over the frequency tuning bandwidth. In spite of that, the MLL based technique is attractive for microwave applications because it avoids the critical phase sensitivity of the PLL method.

Conclusion

Theoretical analysis, simulations and measurements prove that the techniques discussed in this paper can be used to control automatically the frequency response of microwave active filters. The two servomechanisms are suitable to MMIC technology where filters suffer from fluctuations in fabrication process and operating temperature. Measurements show that the central frequency of a microwave active filter accurately tracks the frequency of a reference signal. Other measurements are actually in progress in order to prove the regulation capability of these techniques.

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