# Improved Magnitude Sensitive Detector Structure for Automatically Tuned Filters at Microwave Frequencies

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***Abstract* — In this paper an improved detector structure for an automatically tuned filter that is well suited for application at microwave frequencies is proposed. It can be used in a master-slave structure where the amplitude response of a consecutively detuned master filter at one reference frequency is used to derive a control signal that steers a slave filter in the signal path. The improved detector is analysed theoretically and the result is compared to measured values. It provides good performance at reduced complexity.**

***Index Terms* — Frequency control, tunable filters, microwave filters**

## I. Introduction

The characteristics of analog filters are vulnerable to fabrication tolerances and temperature drift. Automatic frequency control using the popular master-slave approach is the most feasible solution to control these characteristics [1]. It uses a master device that is embedded in a control loop to generate the tuning signal for the slave *Voltage Controlled Filter (VCF)* in the signal path. A good matching between master and slave is essential for a precise operation.

For microwave filters, this problem has been solved in [2], [3] by using a typical phase locked loop based on a voltage controlled oscillator matched to the slave filter.

Another control scheme that uses identical filters for master and slave was proposed in [4] and analysed in detail in [5]. It utilises a test signal to measure either the magnitude response or the phase response of the filter at one reference frequency. The phase sensitive detector showed good performance at the price of higher complexity due to the necessary mixer. In [6] a novel detector was introduced that requires no mixer at the cost of an additional master filter.

In [7] an approach was presented where the amplitude response of one master filter is measured, sampled and stored at different reference frequencies in a time multiplex scheme. A feedback signal is derived from the sampled amplitude values. The various reference frequencies are generated by a frequency synthesiser.

In this paper the concept of an alternating measurement of the master filter is applied to the structure of [6], thereby eliminating the drawbacks of that method because it needs only one master filter. Additionally only one power detector is required and it is operated at the same input power level so that there are no additional inaccuracies due to nonlinearities or insufficient matching between the detectors.

In the following chapter the function principle is explained first. On that basis the new structure is derived and analysed in detail. The results are validated by measurements at microwave frequencies.

## II. The function principle

### A. State of technique

The structure of an automatically tuned filter following the master–slave principle with the detector structure presented in [6] is depicted in Fig. 1. The function is as follows: the control loop in the upper part of the picture adjusts the tuning voltage $u_0$ of the slave filter in such a way that the centre angular frequency $\omega_0$ of the slave filter is tuned to the angular frequency $\omega_r$ of the reference signal. The useful signal of the circuit is filtered by the slave in the lower part.

The crucial component in the control loop is the detector (dashed block in Fig. 1). Its output signal $u_d$ has to reflect the frequency error between the reference angular frequency and the centre angular frequency of the slave filter. It is fed back as the tuning voltage $u_0$ via the control

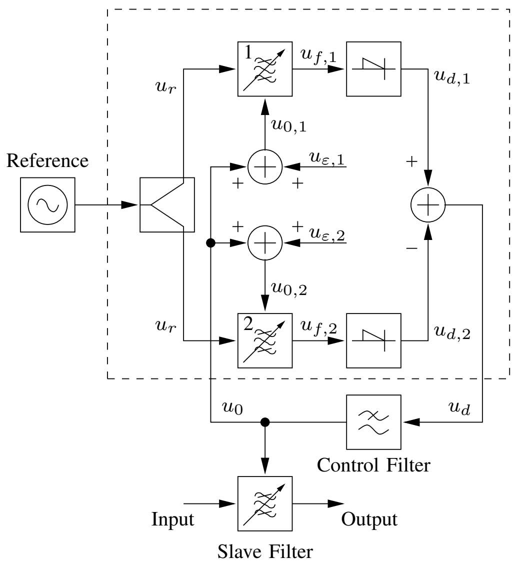


Fig. 1. Structure of the control loop presented in [6]. The circuitry in the dashed box will be called *detector* of the system, the nonlinear blocks represent power detectors.

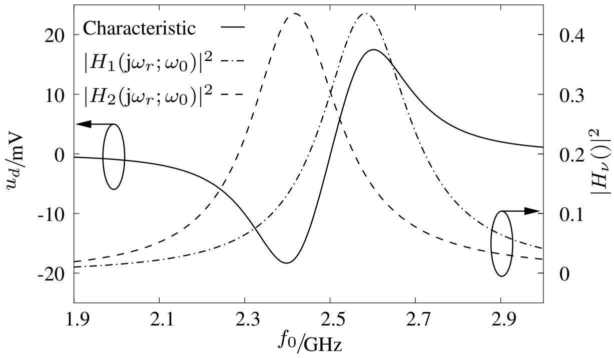


Fig. 2. Magnitude response of the detuned filters and resulting detector characteristic for a linear tuning characteristic of the filter. The passband of the slave filter is around $f_0$. Parameters: $f_0 = {}^{\omega_0}/_{2\pi}$, $f_r = {}^{\omega_r}/_{2\pi} = 2.5\,\mathrm{GHz}$, $A = 0.66$, $Q_0 = 10$, $\omega_{0,0} = 2\pi \cdot 2.25\,\mathrm{GHz}$, $k_f = 1.3 \cdot 10^9\,{}^{\mathrm{rad}}/_{\mathrm{V\,s}}$, $k_p \hat{u}_r^2 = 75\,\mathrm{mV}$, $u_{\varepsilon,2} = -u_{\varepsilon,1} = 0.4\,\mathrm{V}$, $H_\nu(\mathrm{j}\omega_r;\omega_0) = H(\mathrm{j}\omega_r;\omega_0 + \omega_{\varepsilon,\nu})$ .

filter to close the loop.

The sinusoidal reference signal $u_r(t) = \hat{u}_r \cos(\omega_r t)$ with angular frequency $\omega_r$ is applied to both tunable master filters (1 and 2) that have the same properties as the slave filter. Throughout the analysis a second-order band pass filter will be assumed:

$$H(p;\omega_0) = \frac{A\dfrac{p}{\omega_0 Q_0}}{1 + \dfrac{p}{\omega_0 Q_0} + \dfrac{p^2}{\omega_0^2}} \tag{1}$$

with $A$ being the gain at centre frequency, $Q_0 = {}^{\omega_0}/_{\triangle\omega_0}$ and $\triangle\omega_0$ (in ${}^{\mathrm{rad}}/_{\mathrm{s}}$) the relative angular frequency bandwidth at $-3\,\mathrm{dB}$. The relation between the centre angular frequency and the tuning voltage is assumed to be linear for the moment. It is given by $\omega_0(t) = \omega_{0,0} + k_f u_0(t)$ with the VCF conversion factor $k_f$ (in ${}^{\mathrm{rad}}/_{\mathrm{V\,s}}$) and the quiescent angular frequency $\omega_{0,0}$ .

The master filters are detuned compared to the slave filter by the voltages $u_{\varepsilon 1}$, $u_{\varepsilon 2}$. For a linear tuning characteristic of the filters the detuning is proportional to the offset voltages:

$$\omega_{0,\nu} = \omega_{0,0} + k_f(u_0 + u_{\varepsilon,\nu}) = \omega_0 + \omega_{\varepsilon,\nu}\,, \tag{2}$$

$$\omega_{\varepsilon,\nu} = k_f\, u_{\varepsilon,\nu}\,, \qquad \nu \in \{1,2\}\,. \tag{3}$$

The power of the filtered reference signals is converted to proportional DC signals that are subtracted. The power detectors are modelled by $u_{d,\nu} = k_p \hat{u}_{f,\nu}^2$ with $k_p$ (in ${}^{1}/_{\mathrm{V}}$) being a proportionality constant of the power detector.

Fig. 2 exemplifies the principle. The characteristic of the detector has the typical S-shape of a phase sensitive detector. The zero crossing is close to the reference frequency.

### B. New detector structure

Fig. 3 shows the block circuit diagram of the improved detector structure. Instead of two detuned master filters there is only one filter that is successively detuned to an upper and to a lower passband frequency compared to the slave. The power of the filtered signal is converted to a proportional voltage and stored in the sample and hold circuits S/H. The rest of the control loop is like in Fig. 1.

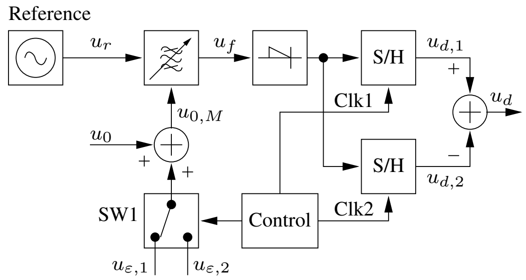


Fig. 3. Block circuit diagram of the improved detector structure.

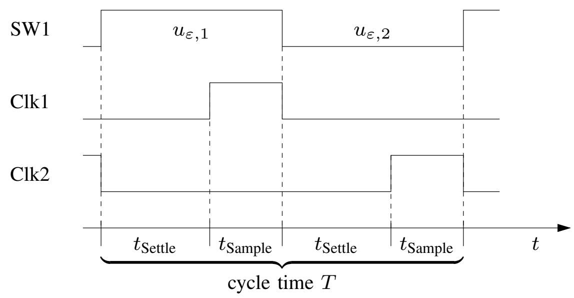


Fig. 4. Timing diagram if the improved detector circuit (Fig. 3). The sample and hold stages are activated with a delay of $t_{\mathrm{Settle}}$ after the tuning voltage is switched by SW1 to give the filter, the detector and the signal processing time to settle to the new state.

The timing of the switch and the sample and hold circuits is shown in Fig. 4. After the switch SW1 has changed the control voltage of the filter, there is a short delay $t_{\mathrm{Settle}}$ before the data is sampled to give the filter, the detector and the baseband signal processing time to settle to the new state. The delay avoids additional spurious responses in the control loop due to transient terms.

The multiplexed operation of the detector converts the time continuous control system into a sampled system. As long as the sampling frequency is much higher than the bandwidth of the loop it can be expected to operate similar to the analog system. If that condition is not fulfilled it is necessary to take the time discrete behaviour into account.

### C. Time discrete system

Fig. 5 shows a simplified baseband model of the time discrete control system. It is simplified as compared to Fig. 3 insofar as the interleaved sampling of the two sample and hold circuits is modelled as a sampling at the same time instance.

In the following analysis all variables and functions of the discrete time $\mu$ will be denoted by a tilde. The

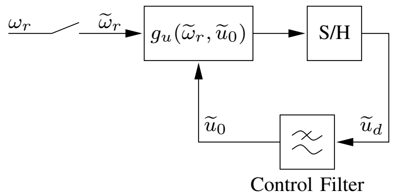


Fig. 5. Baseband model of the time discrete system. The block labelled by $g_u(\widetilde{\omega}_r, \widetilde{u}_0)$ models the detector circuit.

conjunction to the time continuous quantities is given by

$$\widetilde{u}(\mu) = u(t = \mu T)\,. \qquad (4)$$

The function block $g_u(\widetilde{\omega}_r, \widetilde{u}_0)$ models the baseband behaviour of the detector in the dashed box of Fig. 1. Its input quantities are the sampled reference angular frequency $\widetilde{\omega}_r$ and the tuning voltage $\widetilde{u}_0$. This relation holds true, no matter if the signals are time discrete or time-continuous, as long as the settling of the master filter can be neglected. The detector output signal is sampled at equally spaced time intervals $T$ and held constant for the rest of the interval. Even though the control filter is still a time continuous filter, the loop can be analysed as a time discrete system [8].

The analysis follows the procedure described in [5]. Again the tuning characteristic of the filter is approximated by a square root function

$$\omega_0 = v(u_0) = 2\pi \cdot 10^9 \frac{1}{\mathrm{s}} \left( c_0 + c_1 \sqrt{\frac{u_0}{\mathrm{V}}} \right) . \qquad (5)$$

For the control filter, an ideal integrator is assumed with the transfer function

$$H_{\mathrm{RF}}(p) = \frac{b_0}{p} \qquad (6)$$

in the Laplace domain.

All the signals in the baseband model are constant in the steady state. The sampling does not alter the static behaviour in any way, hence the results of the time continuous analysis hold true here as well.

It has been shown previously that the steady states, also called *operating points (OP)* of the control system, are given by the zero crossings of the characteristic $g_u(\omega_r, u_0)$.

The stability behaviour of the steady states is determined using a model that is linearised in the vicinity of the operating point, in which

$$K_v = \left. \frac{\partial g_u}{\partial u_0} \right|_{\mathrm{OP}} \qquad (7)$$

is the slope of the characteristic in the OP.

The z-transform of the time discrete impulse response of the system is given by

$$\widetilde{H}_s(z) = \frac{K_v \widetilde{H}_{\mathrm{RF}}(z)}{1 - K_v \widetilde{H}_{\mathrm{RF}}(z)} = \frac{K_v b_0 T}{z - 1 - K_v b_0 T}\,, \qquad (8)$$

hence a stable operating point is achieved for

$$-2 < K_v\, b_0\, T < 0\,. \qquad (9)$$

In the time continuous case the stability condition was $K_v b_0 < 0$. The sampling adds an upper limit to the gain in the loop.

A vivid interpretation of the stability boundaries is given by the time discrete step response of the linearised system:

$$\widetilde{h}_s(\mu) * \widetilde{\varepsilon}(\mu) = \left( (1 + K_v b_0 T)^{\mu} - 1 \right) \widetilde{\varepsilon}(\mu) \qquad (10)$$

with $\widetilde{\varepsilon}(\mu)$ being the unit step function.

For $-1 < K_v b_0 T < 0$ the sequence approaches the final value monotonously, while for $-2 < K_v b_0 T < -1$ it is an alternating sequence. The shortest settling could be achieved for $K_v b_0 T = -1$, but as the parameter $K_v$ slightly depends on the operating point the condition cannot be met exactly in every point. Nevertheless it is a good value for the loop gain.

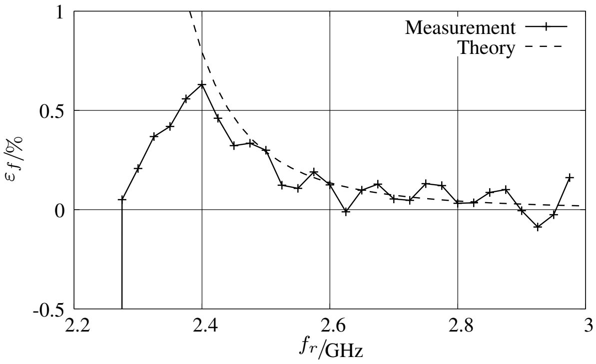


Fig. 6. Relative frequency error in the steady state. Comparison between the analytical and the measured results. Below the reference frequency $f_r = 2.35\,\mathrm{GHz}$ the system does not operate correctly as the tuning voltage of the filter is negative for parts of the cycle. Parameters: $f_0 = {}^{\omega_0}/_{2\pi}$, $f_r = {}^{\omega_r}/_{2\pi}$, $\varepsilon_f = {}^{f_0}/_{f_r} - 1$, $A = 0.66$, $Q_0 = 10$, $k_p \hat{u}_r^2 = 75\,\mathrm{mV}$, $b_0 = -3.1 \cdot 10^4\,\mathrm{s}^{-1}$, $T = 18\,\mu\mathrm{s}$, $u_{\varepsilon,2} = -u_{\varepsilon,1} = 0.4\,\mathrm{V}$, $c_0 = 2.1561$, $c_1 = 0.3392$.

The results of the theoretical analysis were confirmed in a simulation using Matlab/Simulink®. Additionally the time-interleaved sampling that was not considered in the theoretical analysis was also included in the simulations. The system showed stable behaviour within the predicted range of values. It stayed even stable for slightly larger values of $|K_v b_0 T|$.

## III. Measurements

A system was implemented to validate the analytical results. The filter was built up as a first order parallel coupled filter with a varactor diode in the middle of the resonator using microstrip technology.

The filter is tunable in a range from 2.2 GHz to 3 GHz. It has a quality factor of $Q_0 = 10$ and 3.6 dB attenuation in the passband at 2.5 GHz.

The parameter $k_p \hat{u}_r^2 = 75\,\mathrm{mV}$ that was used in the analysis was derived from the realised system at an input power level of $-7\,\mathrm{dBm}$ with $f_r = 2.5\,\mathrm{GHz}$. It was $u_{\varepsilon,2} = -u_{\varepsilon,1} = 0.4\,\mathrm{V}$ resulting in a detuning of the filters by 140 MHz.

The power detector was built up using a zero bias Schottky diode and a transmission line matching network.

The minimum cycle time $T$ was primarily dictated by the speed of the operational amplifiers and the sample and hold circuit in the baseband signal processing. It was chosen to $T = 18\,\mu\mathrm{s}$, the parameter $b_0$ was chosen in order to obtain $K_v b_0 T \approx -1$.

Fig. 6 shows the relative frequency deviation

$$\varepsilon_f = \frac{f_0 - f_r}{f_r} \qquad (11)$$

of the measurement together with the results of the theoretical analysis. Above of the reference frequency $f_r = 2.4\,\mathrm{GHz}$ theory and measurement are in good agreement. The deviations at lower frequencies have two reasons. First, the simple square root approximation from eq. (5) does not reflect the behaviour of the filter well enough for small tuning voltages $u_0$. Secondly, below $f_r = 2.35\,\text{GHz}$ the tuning voltage of the master filter becomes negative during parts of the cycle due to the offset voltage $u_{\varepsilon,1}$. Operation is not useful in that region because the varactor diode is biased in forward direction.

The tuning voltage $u_0$ is used to steer the centre frequency of the slave filter. Some attention has to be paid to the proper rejection of spurious clock signals as they could interact with the wanted filtered signal.

## IV. Conclusion

In this paper an improved magnitude sensitive detector structure for an automatic frequency control system for tunable filters was proposed. It provides the same properties as the system presented in [6] with reduced complexity. It requires only one master filter and one power detector at microwave frequencies, the rest of the control loop operates at baseband frequencies.

During normal operation there is always the same power level applied to the power detector. Hence nonlinearities in its conversion behaviour do not affect the precision of the control system. Furthermore, its behaviour does not have to be matched to a second device.

The analysis predicts a good performance of the system. Measurements at microwave frequencies confirm the theoretical results.

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