OPTIMIZATION OF NOISE PERFORMANCE FOR VARIOUS TOPOLOGIES OF MICROWAVE ACTIVE RECURSIVE FILTERS

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Abstract :

This article deals with the improvement of the noise figure for three topologies of microwave active recursive filters. We show how, using a noise wave formalism [1], the noise factor of these filters can be effectively minimized by using appropriate unbalanced power dividers/combiners and an amplifier. A comparison between the different topologies is given. We start from measured results and validate our approach with simulated examples.

I - Introduction

With the rapid expansion of new applications, such as mobile communications, microwave engineers have found great advantage in using active filters. Nevertheless, the use of active elements in microwave systems has introduced new design parameters and problems such as electrical stability, power handling behavior and noise figure. Among all the existing structures, recursive and transversal filters have recently appeared as a promising solution to filtering problems. A first-order filter has been implemented [2] on a 100µm-thick GaAs substrate using a MMIC design process (figure 1). Since noise performances were not considered during the different design steps, we obviously obtained a poor noise factor of 11.7dB (figure 2).

The objective here is to find which of the three possible topologies achieves the best noise performance by analytically calculate the noise factors using a noise wave formalism. For each topology, we also determine the values of the optimal couplings and of the gain needed to obtain the minimum noise factor.

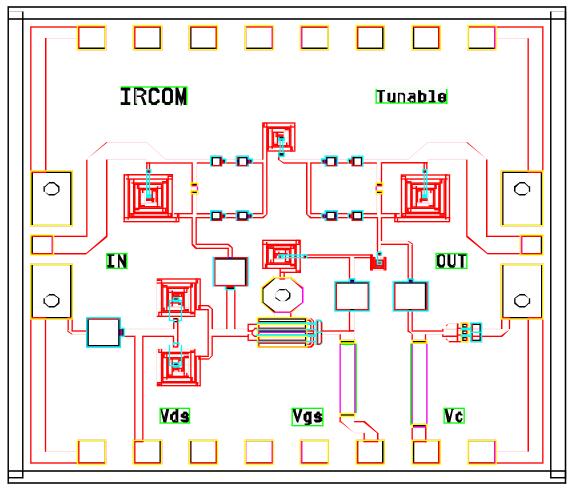

Figure 1 : *Layout of the first-order active recursive filter (GaAs substrate 2x2 mm)*

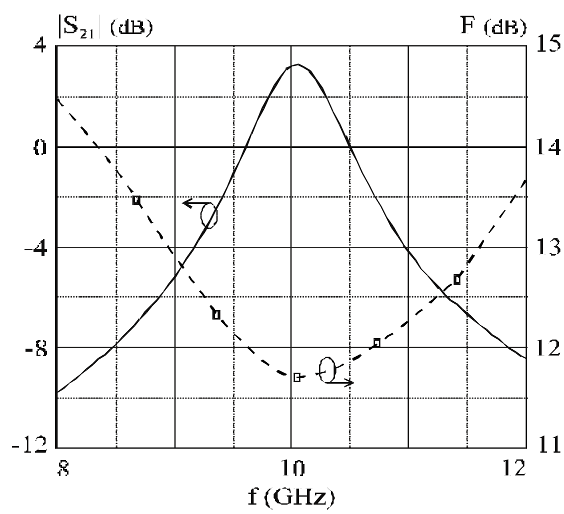

Figure 2 : *Measured S_{21} and noise figure of a MMIC first-order recursive filter*

II-Minimum noise factor for three topologies of microwaves active recursive filters

Feasibility of first-order recursive filters is derived from digital low frequency concepts. Expression (1), where x(t) [y(t)] is the input [output] of the system, shows the time-domain equation of a first-order structure :

$$y(t) = a_0 x(t) - b_1 y(t-\tau) \qquad (1)$$

The corresponding transfer function in the z-notation is given by :

$$H(Z) = \frac{a_0}{\left(1 + b_1 Z^{-1}\right)} \quad \text{where } Z = e^{-2j\pi f\tau}$$

$\tau = 1/f_o$ is the delay-time of the filter and f_o is the central frequency.

To calculate the noise factor, we use the noise wave formalism of [1]. This method consists in modeling the noise of a two-port device with internal noise wave generators c_1 and c_2. Their contribution to the scattering waves b_1 and b_2 can be expressed in the following manner :

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}_Q \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

where S is the scattering matrix of the two-port Q.

To calculate the minimum noise factors of the three topologies, we first define the R and V parameters to set the filtering performances of the filter which must not be modified by the improvement process of the noise factor.

$$R = \frac{|S_{21}|_{max}}{|S_{21}|_{min}} = \frac{|S_{21}(f_0)|}{|S_{21}(f_0/2)|} \quad \text{and} \quad V = \frac{R-1}{R+1}$$

where f_o is the central frequency of the filter.

In order to get the same filtering performances, the three topologies have to be characterized by the same V parameter. Two filters can then be considered as equivalent even if they do not achieve the same gain at f_o. Referring to the V parameter, the transfer function of the three topologies can then be expressed as follows :

$$H_i(Z) = \frac{K_i}{1 - VZ^{-1}}$$

II.1 - <u>Topology 1 :</u> (figure 3)

Initially, we suppose $G = G_o\, e^{-2j\pi f\tau}$ with G_o a positive real gain value and τ the delay-time of the filter. The transfer function is given by :

$$H_1(f) = \frac{\alpha_1 \alpha_2}{1 - G\beta_1\beta_2}.$$

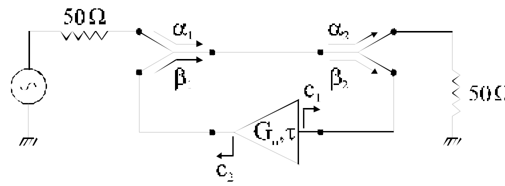

Figure 3 : *Topology 1*
Amplifier placed within the feedback branch

At f_o, the central frequency of the filter, the noise factor is given by (2), with F_A is the noise factor of the amplifier derived from the same noise wave formalism and b_g is the noise wave due to the source resistance at the input port of the filter.

$$F_1 = 1 + \left(\frac{\beta_1}{\alpha_1}\right)^2 (F_A - 1)\ G_o^{\,2} + \left(\frac{\beta_2 - \beta_1 G_o}{\alpha_1\alpha_2}\right)^2 \quad (2)$$

In this case, $V=\beta_1\beta_2 G_o$, $\alpha_1^2+\beta_1^2 = 1$, $\alpha_2^2+\beta_2^2 = 1$. We can find an expression of F_1 as a function of V, β_1, G_o and F_A. An analytical study enables us to determine the expression of β_{1opt}, for which we obtain the minimal noise factor. We can then deduce β_2, α_1, and α_2. It can be shown that for $\beta_1=\beta_{1opt}$, F_1 decreases when G_o increases. So the limit value of F_1, when F_A is kept constant, is given by :

$$\lim_{G_o\to\infty} F_1 = 1 + V^2 (F_A + 1) - 2V + 2V\sqrt{F_A}\,(1 - V)$$

and $\lim_{G_o\to\infty} F_1 < F_A$

This is particularly interesting in the case where we can choose between two amplifiers of same noise factor but with different gain values. Moreover we can obtain, at the resonance frequency f_o, a noise factor of the filter lower than the one of the amplifier used.

II.2 - <u>Topology 2 :</u> (figure 4)

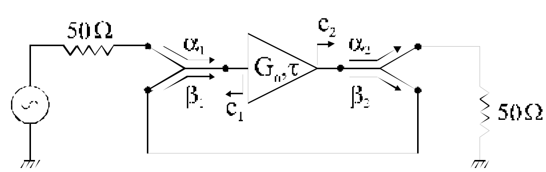

Figure 4 : *Topology 2*
Amplifier placed within the forward branch

The transfer function $H_2(f)$ and the corresponding noise factor F_2 are given by :

$$H_2(f) = \frac{G\alpha_1\alpha_2}{1 - G\beta_1\beta_2}$$

$$F_2 = 1 + \frac{(F_A - 1)}{\alpha_1^2} + \left(\frac{\beta_2 - \beta_1 G_o}{\alpha_1 \alpha_2 G_o} \right)^2$$

With the same method than for topology 1, we find that the expression of β_{1opt} is the same as for topology 1 but with $F_2 > F_1$ at f_o. We notice :

$$\lim_{G_o \to \infty} F_2 = F_A$$

and that the noise factor of the filter cannot be less than F_A.

II.3 - <u>Topology 3 :</u> (figure 5)

The corresponding transfer function $H_3(f)$ and the noise factor F_3 are given by :

$$H_3(f) = \frac{G\alpha_1\alpha_2}{1 - \beta_1\beta_2 e^{-2j\pi f\tau}} = GH(f)$$

$$F_3 = F_A + \frac{1 - |H(f)|^2}{G_o |H(f)|^2}$$

where H(f) is the transfert function of a passive filter. In this case $V = \beta_1\beta_2$. With the same method we obtain :

$$\beta_{1opt} = \sqrt{V} \Rightarrow \beta_{2opt} = \frac{V}{\beta_{1opt}} = \sqrt{V} = \beta_{1opt}$$

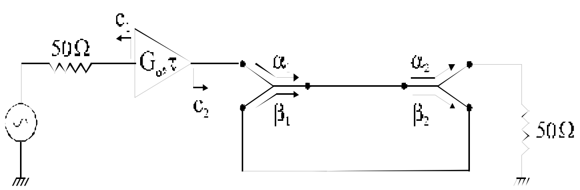

Figure 5: *Topology 3*
Amplifier cascaded with a passive filter

F_3 is minimum when the couplers are identical. Moreover for this topology :

$$\lim_{G_o \to \infty} F_3 = F_A$$

leading to the same remarks than for topology 2.

III - <u>Comparison of the three topologies</u>

To compare the topologies, we consider that the same amplifier is used with the same noise factor and gain values and we also consider that the three topologies are optimum in terms of noise ($\beta_1 = \beta_{1opt}$) and achieve the same filtering performance V. It can be analytically derived, thanks to the software Maple V [3], that :

$$\begin{cases} F_3 < F_1 < F_2 & \text{if } 1 < G_o < G_{lim} \\ F_1 < F_3 < F_2 & \text{if } G_o > G_{lim} \end{cases}$$

$$\text{with} : G_{lim} = \frac{V}{(1-V)} \sqrt{\frac{F_A(V+1) + (1-V) + 2\sqrt{F_A}}{F_A(V+1)^2 - (V-1)^2}}$$

for which $F_3 = F_1 = F_2$ at f_o.

We can then say that topology 2 is the worst topology for noise and that the choice between topology 1 and 3 depends on V and the gain G_o of the amplifier. Besides, an important advantage of topology 1 is that this topology is the most interesting regarding to power handling behavior because the amplifier is placed within the feedback branch and see at its input less power. So topology 1 can be considered as the best solution for our problem.

IV - <u>Validation examples</u>

Using a microwave CAD software, we present three examples to validate our calculations.

IV.1 - <u>Example 1 : $G_o = 1.316$, $F_A = 9.3$ dB, R = 5 (V = 2/3), $G_{lim} = 1.2$, $G_o > G_{lim}$</u>

The values of G_o, F_A and R, correspond to the ones used in the filters already realized using MMIC technology (figures 1 and 2). We notice that the optimum noise factor decreases down to 8.47 dB less than F_A (table 1).

	β_{1opt} (dB)	β_2 (dB)	$F(f_o)$ (dB)	simulated results
topology 1	-5.12	-0.76	8.46	figure 6
topology 2	-5.12	-0.76	10.75	
topology 3	-1.76	-1.76	9.28	

Table 1 : $G_o > G_{lim} \Rightarrow F_1 < F_3 < F_2$ *at* f_o $

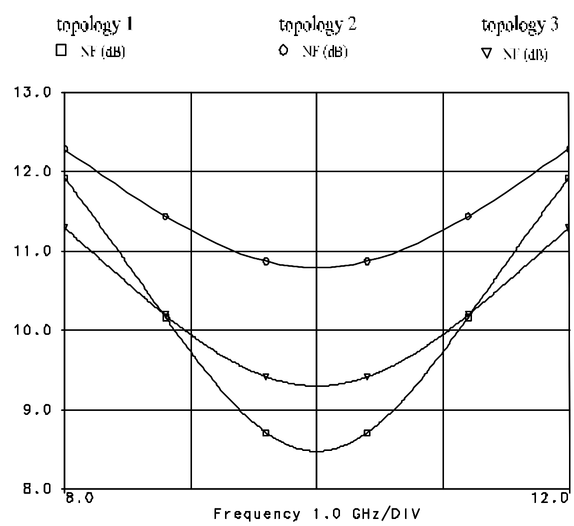

Figure 6: *Simulated noise figures for example 1 :* $G_o > G_{lim} \Rightarrow F_1 < F_3 < F_2$ *at* f_o

IV.2 - Example 2 : $G_o = 1.316$, $F_A = 9.3$ dB, R = 10 (V = 0.82), $G_{lim} = 1.8$, $G_o < G_{lim}$

We now try to built more selective filters with the same amplifier. We set R=10 (V=0.82), and in this case $G_o<G_{lim}$ leading to $F_3< F_1< F_2$ (table 2) as expected. With examples 1 and 2, we also notice hat the noise factors increase when selectivity increases.

	β_{1opt} (dB)	β_2 (dB)	$F(f_o)$ (dB)	simulated results
topology 1	-3.88	-0.25	10.2	figure 7
topology 2	-3.88	-0.25	11.44	
topology 3	-0.87	-0.87	9.35	

Table 2 : $G_o<G_{lim} \Rightarrow F_3< F_1< F_2$ at f_o

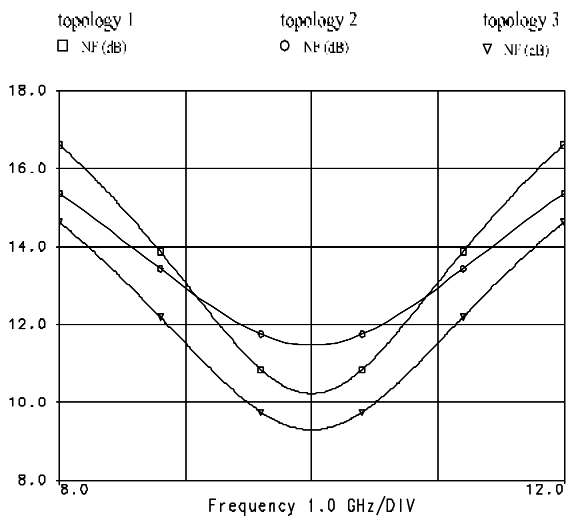

Figure 7: *Simulated noise figures for example 2 : $G_o<G_{lim} \Rightarrow F_3< F_1< F_2$ at f_o*

IV.3 - Example 3 : $G_o = 2$, $F_A = 9.3$ dB, R = 10 (V = 0.82), $G_{lim} = 1.8$, $G_o > G_{lim}$

In this case, we keep R=10 but we increase the gain (G_o = 2), which leads to $G_o>G_{lim}$. We obtain F_1=8.91 dB, F_2=10.07 dB and F_3=9.28 dB (figure 8). This shows that if the gain is increased (for the same F_A) the noise factor of the filter decreases as expected.

Conclusion

In this article, we have analytically analyzed three different topologies of microwave active recursive filters using the same active elements. We have derived, using a noise wave formalism, the analytical expressions of the noise factor of each topology. We have also shown the existence of optimal coupling values, which achieve minimum noise factors.

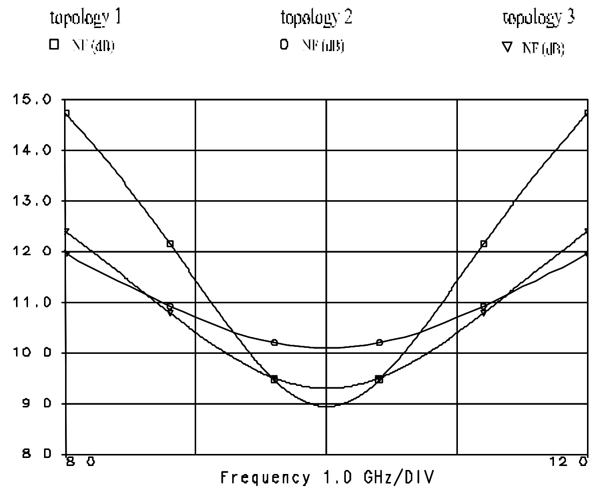

Figure 8: *Simulated noise figures for example 3 : $G_o>G_{lim} \Rightarrow F_1< F_3< F_2$ at f_o*

The most important result is that with the first of the three topologies, when the amplifier is placed in the feedback branch, the noise factor of the filter could be less than the one of the amplifier used. This result shows that recursive structures are promising solution to low noise filtering problem even better than the classical cascade approach of an amplifier with a passive filter structure. We have also studied the influence of the value of the gain upon the noise factor of the three topologies and validated our analysis and results with different simulated examples.

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