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NOISE PERFORMANCES OPTIMIZATION OF GAAS MONOLITHIC MICROWAVE ACTIVE RECURSIVE FILTERS USING NOISE WAVE TECHNIQUES

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Abstract

This article deals with the improvement of noise figure for microwave active recursive filters. We show, using a noise wave analysis [1], how the noise factor of a first-order recursive structure can be effectively minimized, by using appropriate unbalanced power dividers/combiners in association with an amplifier of given gain and noise factor values. We start from measured results of monolithic filters and validate our approach with simulated examples.

Introduction

With the rapid expansion of new applications, for example 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 behaviour and noise figure. Among all the existing structures, recursive and transversal filters have recently appeared as a promising solution to filtering problems with the implementation both in hybrid and monolithic technologies [2], even for high-order responses using a cascade association of first-order unitary filters [3]. However, the noise factor of such structures, as will be shown further with measurement results, can be poor if noise performances have not been considered during the design steps.

The objective here is to analytically demonstrate that noise factor of recursive structures can be greatly minimized using a noise wave formalism. Simulation results validate our approach and prove the capability of recursive structures to be possibly used as first-stage low-noise reception filters.

I - Noise wave formalism

Using a noise wave formalism [1], a linear two-port is described by noise waves and scattering parameters. The noise waves are time-varying complex random variables characterized by an Hermitian matrix which components are referred to as noise waves parameters.These noise waves contribute to the scattered waves b_1 and b_2 relatively to the following expression :

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

The noise factor of the two-port is then defined as the following ratio :

$$F = \frac{(P_S + P_Q)}{P_S} = 1 + \frac{P_Q}{P_S}$$

where P_S is the noise power at the output of Q due to the source generator,
P_Q is the noise power at the output of Q due to the quadripole Q,

II - First-order recursive filter

Feasibility of first-order recursive filters, derived from digital low frequency concepts, is now well-established both in hybrid and MMIC technologies [2]. 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 in (2) where $z = e^{2j\pi f\tau}$.

$$H(z) = \frac{a_0}{1 + b_1 z^{-1}} \qquad (2)$$

Preserving low frequency principles, implementation of the structure at microwaves is presented in figure 1 and requires three different blocks matched to 50Ω : one delay component τ, an amplifier G as a weighting parameter and two power dividers/combiners for the signal summation within the structure [2]. Recently, this first-order filter has been implemented [2][3] on a 100μm-thick GaAs substrate using a MMIC design process.

Figure 2 presents the measured S_{21} parameter of the filter and the corresponding noise factor in the 8-12 GHz range. These results were obtained using 3dB power dividers/combiners, and an amplifier of gain value G=1.316 (2.4dB). Since noise performances were not considered during the different design steps, we clearly obtain a poor noise factor of 11.7 dB at the center frequency $f_0 = 1/(2\tau) = 10$ GHz. Noise factor of the amplifier at the same frequency has been estimated of about 9.5 dB using a CAD software.

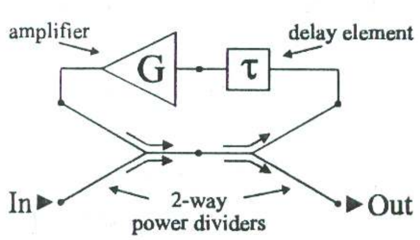

Figure 1 : Topology of a first-order filter at microwaves using blocks matched to 50Ω

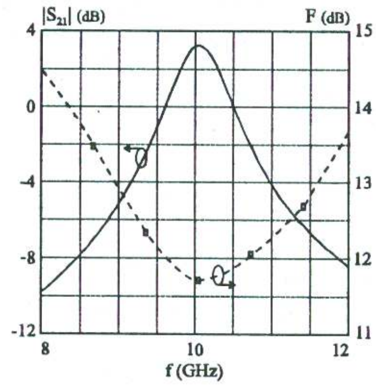

Figure 2 : Measured S_{21} and noise factor of a MMIC first-order recursive filter

III - Noise factor of first-order topologies

Using the same approach, we now consider two topologies in figure 3, that can lead to first-order recursive responses, both using two different unbalanced lossless power dividers/combiners, each one characterized by two coupling coefficients α_i and β_i (with $|\alpha_i|^2 + |\beta_i|^2 = 1$).

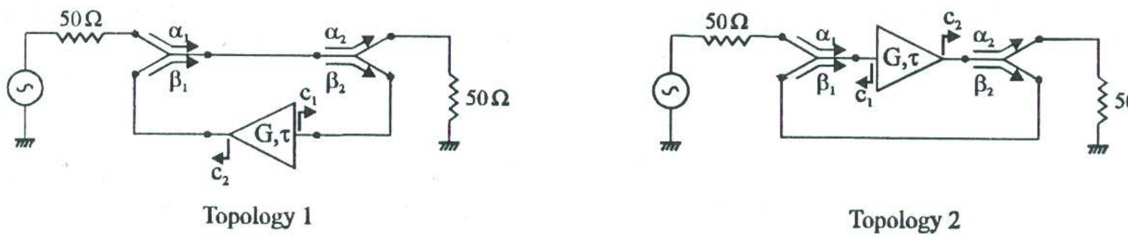

Figure 3 : First-order recursive filter topologies using noise wave technique

The corresponding responses in the z-notation and noise factors using the noise wave technique are :

$$H_1(z) = \frac{\alpha_1 \alpha_2}{1 - \beta_1 \beta_2 G z^{-1}} \qquad H_2(z) = \frac{\alpha_1 \alpha_2 G}{1 - \beta_1 \beta_2 G z^{-1}}$$

$$F_1 = 1 + \left|\frac{\beta_1}{\alpha_1}\right|^2 \cdot \frac{\left|\overline{c_2}\right|^2}{\left|b_g\right|^2} \qquad F_2 = 1 + \left|\frac{1}{\alpha_1 G}\right|^2 \cdot \frac{\left|\overline{c_2}\right|^2}{\left|b_g\right|^2}$$

The noise factors can also be expressed as a function of F_A, the noise factor of the amplifier derived from the same noise wave approach, as :

$$F_1 = 1+\left|\frac{\beta_1}{\alpha_1}\right|^2 \cdot (F_A - 1)|G|^2 \qquad\qquad F_2 = 1+\frac{F_A - 1}{|\alpha_1|^2}$$

Note that F_1 and F_2 only depend on the coupling values of the input coupler of the filter.

Initially, when using two 3dB couplers, a positive and real gain value G is determined for a bandpass response, considering the expected filtering performances of the structure given by the ratio :

$$\frac{|S_{21}|_{Max}}{|S_{21}|_{Min}} = \frac{|S_{21}(f_0)|}{|S_{21}(3f_0/4)|} = \frac{1+G/2}{1-G/2} \qquad f_0=1/\tau \quad \textit{(see (1))}$$

With the last example of paragraph II, this ratio is near 5 (14 dB) and the objective is to find for the two topologies, the values of the four coupling parameters $[\alpha_1 ; \beta_1 ; \alpha_2 ; \beta_2]$ to reach, with the same amplifier, the same filtering performances (i.e. the same ratio) when trying to minimize the noise factor of the structure. We then have $\beta_1\beta_2 = 1/2$ to obtain the same performance ratio (with $0 < \beta_{1,2} < 1$ and $G < 2$ for electrical stability [2]).

The problem is first, to know for each topology, how to choose β_1 to minimize the corresponding noise factor, and on the other hand, for a given value of β_1, which topology achieves the lowest noise factor value. It can be analytically demonstrated that, for the two topologies, β_1 must be chosen as small as possible but cannot be lower than 1/2. It can also be derived that $F_1 < F_2$ when $\beta_1 < 1/G$ (3).

IV - Examples

Using the same amplifier (G=1.316 ; F_A=9.5 dB), we give three examples to validate our approach.

Example 1 (figure 4) :
We verify here that, with 3dB couplers, topology 2 gives a greater noise factor than topology 1 when $\beta_1 = 0.707$, that is $\beta_1 < 1/G$ (0.76). In this case, calculation and simulation gives a 12.3 dB value for F_2 greater than the measured 11.7 dB for topology 1.

Example 2 (figure 5) :
We verify now that $F_1 = F_2$ when $\beta_1 = 1/G$. Calculation and simulation gives a 13 dB value for $F_{1,2}$ greater than in example 1 because β_1 is greater in this case.

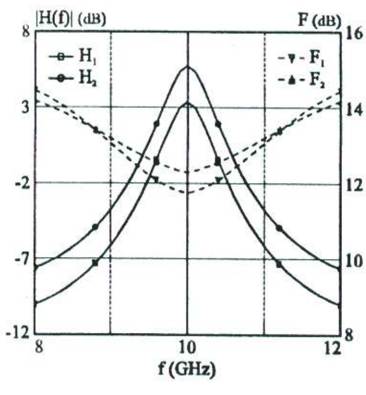

Figure 4 : Example 1
$\beta_1 < 1/G$ ($\beta_1 = 0.707$) $\Rightarrow F_2 > F_1$

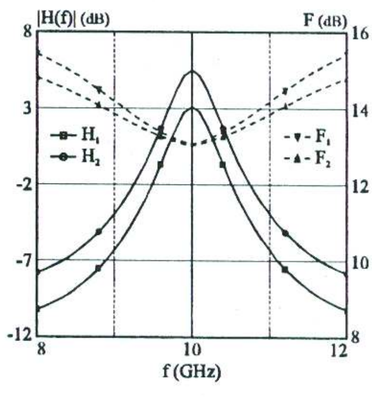

Figure 5 : Example 2
$\beta_1 = 1/G = 0.76 \Rightarrow F_2 = F_1$

Example 3 (figure 6) :

With $\beta_1 = \beta_{1\,min} = 1/2$, the theoretical noise factor $F_{1\,min}$ would be of 7.5 dB, much less than the 9.5 dB noise factor of the amplifier. But this leads to a non physical case with $\beta_2 = 1$ and $\alpha_2 = 0$. So we take $\beta_1 = 0.6$. Calculation and simulation gives $F_1 = 9.4$ dB nearly equal to F_A the noise factor of the amplifier. The $S_{21\,Max}$ value is 2.2 dB, only 1dB less than in the initial case with 3 dB couplers.

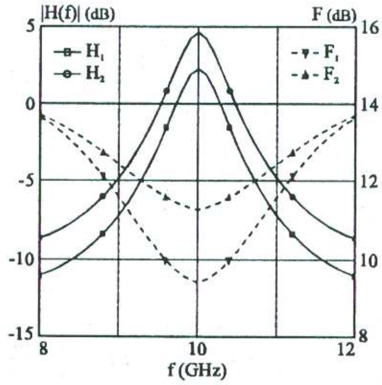

Figure 6 : Example 3
$\beta_1 = 0.6 \Rightarrow F_1 \rightarrow F_{min}$

We so obtain here, with a single active filter, the same performances as with a classical association filter/low-noise amplifier, and then smaller size for the circuits. The other advantage resides in the fact that, only a part of the input power goes at the input of the amplifier, thus leading to better power results in terms of compression and intermodulation.

Conclusion

In this paper, we have analytically demonstrated and numerically verified, using a noise wave technique, that the noise factor of a first-order recursive filter could be easily minimized by choosing appropriate coupling values for the two passive power dividers/combiners associated with an amplifier of fixed gain and noise factor values. The fact we can obtain a noise factor lower than that of the amplifier used, tends to classify recursive structures as a promising alternative solution to the classical use of a high-gain low-noise amplifiers. Moreover, high-order low-noise recursive filter design will become possible, employing the cascade association of first-order recursive cells [3] which noise performances have been optimized with this technique.

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