Novel Adaptive Predistortion Technique for Cross Coupled Filters

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ABSTRACT — **This paper presents a novel adaptive predistortion technique for general cross-coupled microwave/RF filters with improved insertion loss and group delay equalization. The method enables many potential applications of an almost abandoned technique, especially using a lower Q design to emulate the performance of a higher Q filter. A 10-4-4 coaxial filter was built to verify the validity of the new method. The technique should lead to practical applications such as satellite transponder input multiplexers.**

I. INTRODUCTION

Cross-coupled microwave and RF filters are used in various communications systems, in particular communications satellites and earth stations. Filter design is usually a trade off between parameters such as insertion loss, loss variation, group delay, isolation, physical dimensions and mass. The approach to the design of microwave filters using different functions expressed often in polynomial form is well documented [1]. Once the material and type of resonator are chosen, the Quality (Q) factor is set. In order to increase the Q, one often must increase the size of the resonators resulting in a larger and heavier filter. This may not always be practical due to overall design constraints driven primarily by the application. The finite Q factor (highest possible value selected after the trade off between size and performance is made) will translate to energy dissipation in the filter due to the insertion loss. The filter will also exhibit finite band edge sharpness related to the particular Q value. In order to improve the parameters such as loss variation, without resorting to an increase in size and mass, an approach using predistortion technique can be used. In the area of microwave filter design, the concept was first proposed by Livingston [2] and later described in more detail by Williams [3] for cross coupled microwave filters (with non-adjacent cavity couplings to realize transmission zeros). It is noted that they both use it to predistort a relatively high Q factor filter. The goal of their contribution was to enhance the filter performance (loss variation) by emulating even much higher Q factor. In [3], the filters used before predistortion exhibit a Q of 8000 (both wave guide and dielectric resonator), which today still represents somewhat the state-of-art in satellite communication systems (thus considered as high Q). Their approach does not change the size and weight of the filter and therefore does not translate to any subsequent reduction in volume and mass.

In the paper [3], the key to predistortion is to move the transmission poles (of the filter function) towards the $j\omega$ axis by a "fixed amount". This technique as described in [2-3] can flatten the loss variation at the severe expense of insertion loss and return loss. Since the last publication in 1985 [3], to the best of our knowledge, there are no other known publications on this subject in the microwave engineering community. We also are not aware of any commercial application utilizing this technique. We believe that the main reason is the impact on insertion loss is too severe for most practical communication systems to absorb, especially if one chooses to design a predistorted filter using relatively low Q factor resonators as presented in the later sections of this contribution. Using a low Q approach, even with the potentially very significant mass and volume saving as described in the next section, the technique [3] would have not taken off the ground because the insertion loss penalty will be even higher. Again, to the best of our knowledge a low Q design approach using predistortion has never been attempted. Another perceived problem with predistorted filter was tuning. With the advances in computer aided tuning technique, the tuning is of less concern today.

In satellite communication applications, group delay equalization is often incorporated in the design process of a filter. The simple predistortion technique disclosed in [2-3] inherently leads to undesirable increase in the group delay ripple because the approach disclosed in [3] did not consider filters with group delay equalization.

High Q factor filters are often used in the input multiplexer (IMUX) assemblies of communication satellite transponders. The most critical electrical parameters for an IMUX are in-band performance such as loss variation and group delay. From a physical perspective, mass and volume are also very critical considerations. The absolute insertion loss in the band center is often a secondary parameter that can be traded off. An IMUX is incorporated in the payload after the low noise amplifiers (LNAs, which are part of the RF receiver). The gain of the low noise amplifiers can be

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varied. By setting the gain to a higher value, the insertion loss increase associated with the predistortion technique can be recovered as long as the LNA has enough gain margins. This contribution makes full use of the possibility of insertion loss trade off by applying a novel predistortion technique to a very low Q factor filter (<3000). This approach does not only improve the performance of the loss variation (with much smaller insertion loss penalty) but also reduces the size and mass significantly.

II. THEORY [4]

In the paper [3], the key to predistortion is to move the transmission poles (of the filter function) towards the j ω axis by a "fixed amount" r ([3], page 402, equation (4), page 403, Fig.2). To illustrate this, let's examine the key formula of the design process:

$$S_{21} = \frac{D(s)}{E(s)} \quad (1)$$

Where S_{21} is a measure of power transmission through the filter. s=jω. ω is the angular frequency. The filter design process generally involves synthesizing the poles and zeros of a rational function S_{21}. The transmission poles are the roots of polynomial E(s) [1].

$$E(s) = c(s - p_1)(s - p_2)....(s - p_n) \quad (2)$$

c is a constant. p_i is the i^{th} root of E(s).

When loss is modeled using the notion of dissipation factor r [3], E(s) take the form:

$$E(s) = c[s - (p_1 - r)]...[s - (p_n - r)] \quad (3)$$

The adaptive predistortion is realized by introducing the adaptive factor a_i (i=1, 2, ... n),

$$E(s) = c[s - (p_1 - r + a_1)]...[s - (p_n - r + a_n)] \quad (4)$$

a_i is an arbitrary factor that can be virtually anything, as long as the law that governs physical realizibility is not broken, .i.e., keep all zeros of E(s) on the left side of complex plane. So

$$real[p_i - r + a_i] < 0 \quad (5)$$

i=1, 2, ..., n. Without loss of generality, a_i is chosen to have the piecewise sinusoidal (shaped) function as shown in Figure 1 (shown as n=5). The starting value of a_i is

$$a_i = 0.1r \sin\left[\frac{(i-1)\pi}{2(n-1)}\right] \quad (6)$$

a_i is adjusted by the optimization algorithm. Using a piecewise sinusoidal function will ensure all a_i is changed at difference pace. This is a general form of mathematical expression to represent any shapes. The method in [3] then becomes a special case when all a_i are the same. The filter response can be calculated once again per [1, 3]. Let's call it F(s). The requirement (including specifications) can be also defined as function R(s). An optimization method such as least square is used to minimize

$$\min|F(s) - R(s)| \quad (7)$$

by adjusting a_i under the condition of (5). A new set of root of E(s) is obtained as

$$t_i = p \ \ - a_i \quad (9)$$

The final filter function takes the form of

$$S_{21}(s) = \frac{D(s)}{E'(s)} \quad (9)$$

where

$$E'(s) = c(s - t_1)(s - t_2)....(s - t_n) \quad (10)$$

There is no change at all for transmission zeros.

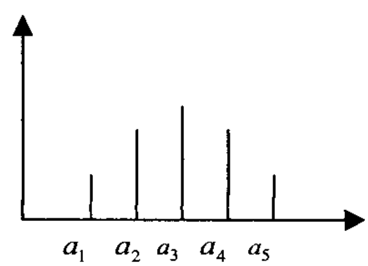

Figure 1. Piecewise sinusoidal function

This adaptive predistortion technique will result in much less insertion loss despite using low Q resonators, while other parameters such as loss variation will also be better than [2-3]. The small increase in group delay ripple (when using [3] for self equalized filter) can also be fixed. In one example, we analyzed a 10^{th} order filter typically used for satellite communications. The resonator used has a Q factor of 3000. The target was to get equivalent performance of a filter with Q of 8000. The results are given in Table 1.

One can notice there is a 1.9 dB improvement on insertion loss and 1.6dB improvement on return loss. Although using any type of predistortion technique always leads to some level of insertion loss penalty, it is always very desirable to minimize the extra insertion loss. As one can see from Table 1, using technique [2, 3] will lead to an additional 5.9dB insertion in a low Q filter using predistortion. On the other hand, using the disclosed method will result in only 4dB loss in addition to a conventional dielectric resonator filter, which has an insertion loss of approximately 1.0dB. This improvement is very significant as it could lead to direct "drop in" type replacement of the current IMUX systems. The increase in LNA gain is within the range of adjustability of the amplifiers and may not require redesign to increase their gain (an extra stage).

Table 1. Case Study

Parameters (dB)	Adaptive Predistortion	Predistortion [3]
Insertion loss	-5.0	-6.9
Return Loss	-3.6	-2.0

III. FILTER REALIZATIONS AND MEASUREMENT

To realize a 10-4-4 filter [1] using the optimization procedure given in the last section, the following 8 transmission zeros are chosen with predistortion factor of 0.021054 (the case given in Table 1):

$$\pm 1.19912j; \quad \pm 1.65389j; \quad \pm 0.61730 \pm 0.34881j$$

One simple solution is to move the first pair of poles near the $j\omega$ axis at 30% less:

$$-0.02867 \pm 1.03745j; \quad -0.13373 \pm 0.95286j$$
$$-0.24175 \pm 0.72560j; \quad -0.26561 \pm 0.43318j$$
$$-0.27692 \pm 0.15092j$$

The coupling matrix derived [1] through this process is presented in Figure 2. It is also interesting to point out that the reflection zeros (S11) will no longer be on the $j\omega$ axis :

$$-0.11968 \pm 0.94621j; \quad -0.22116 \pm 0.72177j$$
$$-0.24443 \pm 0.43250j; \quad -0.25504 \pm 0.15019j$$
$$0.00000 \pm 1.02920j$$

A low cost coaxial resonator structure using 0.5x0.5x0.7in cavities was selected to construct the low Q (Q=3000) filter [4, 5]. The filter is shown in a side-by-side comparison to a typical dielectric resonator filter in Figure 3. The center frequency is 3.952GHz and bandwidth is approximately 36MHz. The larger filter with a Q of 8000 represents what is currently being used for input multiplexers in satellite transponders. Both filters are of the same frequency and order. The volume of smaller coaxial filter is approximately 25% of the larger dielectric filter with a corresponding mass reduction about 65%.

The measured performance of the adaptively predistorted filter is shown in Figure 4-6. Both loss variation and isolation plots in Figure 5 and 6 are normalized to 5dB. The in-band insertion loss variation is less than 0.1dB and the in-band group delay is less than 2ns. This set of measured data clearly confirms that by implementing adaptive predistortion technique, the performance of a low Q coaxial filter as a minimum is comparable (group delay) to or significantly better (loss variation) than a high Q dielectric filter (Q=8000). The method can also be used for high Q filters although the advantage would be less impressive.

IV. CONCLUSION

A novel adaptive predistortion technique has been presented and verified through the design and construction of a practical 10 pole coaxial filter. The new method allows the realization of microwave filters at a lower cost, lighter mass, smaller volume and better performance with minimum insertion loss penalties. The technique should lead to significant improvement for applications [4] such as satellite transponder input multiplexers, where insertion loss can be traded off for in-band flatness, mass and volume.

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R_1=0.16849, R_N=1.31311

-0.00001	0.69284	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.01050
0.69284	0.00000	0.55881	0.00000	0.00000	0.00000	0.00000	0.00000	-0.01916	0.00000
0.00000	0.55881	0.00000	0.51954	0.00000	0.00000	0.00000	-0.05407	0.00000	0.00000
0.00000	0.00000	0.51954	0.00000	0.51651	0.00000	0.08177	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.51651	0.00000	0.50776	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.50776	0.00000	0.54619	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.08177	0.00000	0.54619	0.00000	0.57706	0.00000	0.00000
0.00000	0.00000	-0.05407	0.00000	0.00000	0.00000	0.57706	0.00000	0.67625	0.00000
0.00000	-0.01916	0.00000	0.00000	0.00000	0.00000	0.00000	0.67625	0.00000	1.14591
0.1050	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.14591	0.00000

Figure 2. Coupling matrix for an adaptively predistorted, self equalized 10-pole filter

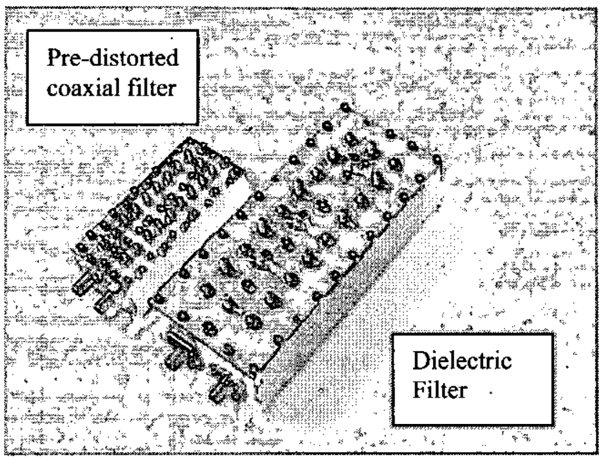

Figure 3. A Coaxial Resonator Predistorted And A Conventional Dielectric Resonator Filter

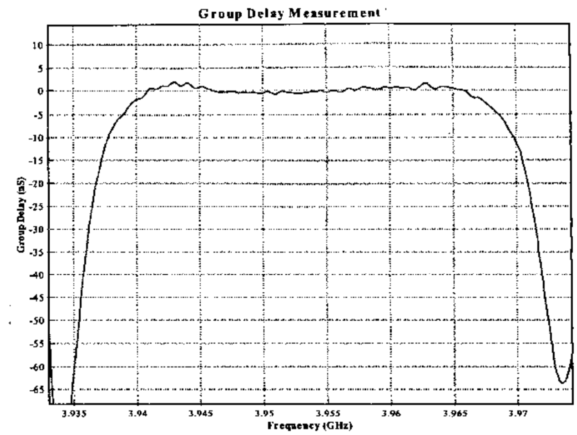

Figure 4. The Measured Group Delay

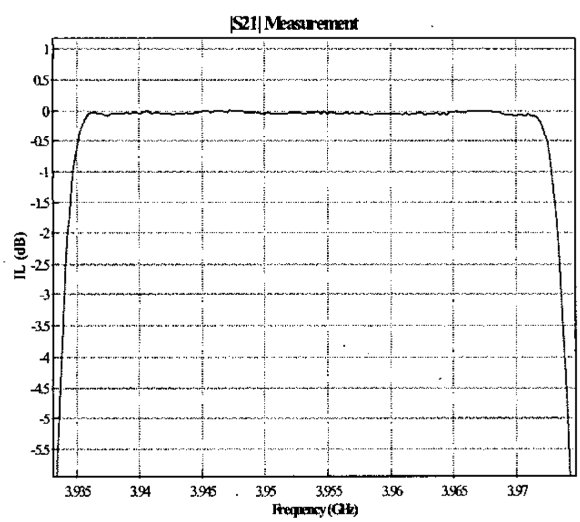

Figure 5. The Measured Loss variation

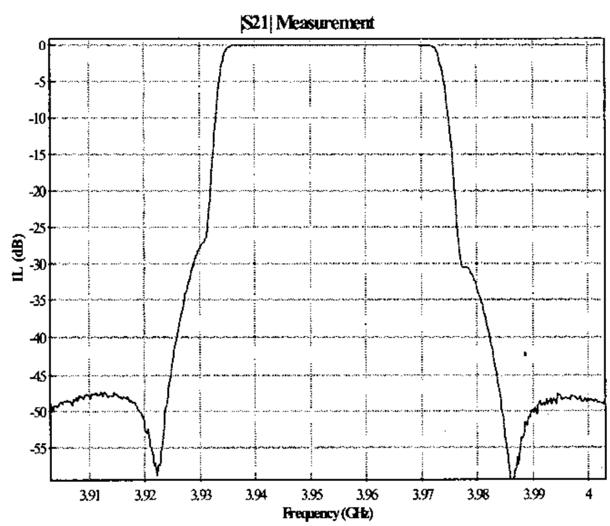

Figure 6. The Measured Isolation