Predistorted Ku-band rectangular waveguide input filter

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***Abstract*— In current Ku-band satellite telecommunication systems usually a working band selection is performed by means of an input filter before the LNA. Moreover, in some architectures more stringent selectivity requirements may be needed in order to reject cross-coupled transmission power signals coming into the reception chain, being necessary an spurious reject filter after the LNA. On the other hand, depending on the near rejection requirements implementing transmission zeros in the filter response maybe needed. However, this also deteriorates in-band response, affecting channels in the extremes of the reception band. In-band response can be improved again by increasing input filter quality factor using predistortion synthesis technique, but at the cost of higher insertion loss and worse reflection response. This work analyses how predistortion technique can be applied to the design of Ku-band rectangular waveguide filters with transmission zeros implemented through cross-couplings in order to improve in-band performances. Moreover, undesired effects arising from applying this technique are also discussed. From authors knowledge, it is the first time this synthesis technique is applied to rectangular waveguide filters with cross-couplings.**

***Index Terms*— predistortion, waveguide filter, ku-band.**

I. Introduction

In satellite communications systems high performance filters are needed in order to reject unwanted signals introducing deleterious effects into the communication chain [1]. Due to the special characteristics of satellite communication systems, where extremely weak signals coming from earth are received while high power signals are transmitted back, highly selective filters are needed. Input filters are used in satellites to select reception band while rejecting transmission band signal leaked into the reception chain. Particularly, input filters used in satellites usually have to provide low loss, high selectivity and a wide spurious free band. Moreover, since the reception band carries several channels, input filter passband flatness is also important in order to minimize deterioration of channels laying at the extremes of the reception band. On the other hand, every equipment used in satellite systems, including filter, is required to have low mass and size, since launch cost is proportional to the overall mass of the satellite. When using classical filter synthesis techniques size/mass and highly selective/flat response are opposite goals. So, it is needed to look for a trade-off between electrical performance and physical dimensions.

The quality factor (Q) parameter measures the quantity of energy released at the output of the filter with respect to the energy at the input [2]. When using classical synthesis techniques there is a direct relationship between quality factor and response passband flatness. In fact, the lower the quality factor the bigger the round off of the response passband. This round off limits the usable bandwidth of the filter. The achievable Q factor is imposed by the technology used to implement resonant cavities composing the filter. Typically, input filters required for Ku-band have been implemented using rectangular in-line topologies with waveguide cavities and classical synthesis techniques [3], [4]. However, as spectrum becomes scarcer applications require more selective and demanding filters. For such applications more complex filters implementing transmission zeros or with higher Qs than those achievable with rectangular waveguide are needed. Current solutions for rectangular waveguide in Ku-band implement transmission zeros by means of cross-couplings in folded topology or using extracted pole topologies. This increases complexity but manufacturing techniques are simple. If a higher Q is needed, cylindrical waveguide becomes an option [5]. Cylindrical cavity dual-mode filters have superior performances with respect to its rectangular cavity counterparts, but at the expense of increasing manufacturing complexity.

For input filter application it would be desirable to increase rectangular cavity filters Q in order to achieve cylindrical cavity filters performances with an easier to manufacture technology. For a certain mode, cavity dimensions are chosen in order to maximize Q while maintaining a wide spurious free range [2] (another mandatory requirement for input filters). Due to higher order modes, mode selection is quite limited to modes with Q around 5000 in Ku-band, in contrast with 10000 in cylindrical cavities.

Recently, novel synthesis methods exploiting predistortion techniques have been proposed [6], [7], and applied to the design of more compact filters [8]. Another approach (followed in this work) is to use this techniques to design filters showing flatter passbands. This is somehow equivalent to design a filter with classical techniques considering a higher Q. For this reason, the concept of effective quality factor Q_{eff} is introduced for predistorted filters to indicate the Q that a classical filter must provide in order to show the same passband flatness. However, due to physical limitations, this improvement in the Q produces an increase of the filter insertion losses and a degradation of return losses. As will be shown later both problems could be addressed fairly straightforward in Ku-band communication payloads.

II. Filter Design

A. Circuital Design

Classic filter synthesis techniques assume that filters are composed of non-dissipative elements (lossless prototype filter). However, in practice filters are made of distributed elements that show some losses. These losses are described by the unloaded quality factor Q_u, which in the lossless synthesis is assumed to be infinite. If a finite Q_u is considered in the synthesis, then it is equivalent to add a positive real factor δ to the purely imaginary frequency variable $s = j\omega$.

$$\delta = \frac{f_c}{BW}\frac{1}{Q_u} \tag{1}$$

This shifts singularities of the filtering function (poles and zeros) away from the imaginary axis, so that in-band insertion losses arise and reflection and transmission responses are distorted appearing a round-off in the transmission response.

Classical predistortion synthesis technique allows high-performance filtering responses using low Q resonators. This is achieved by modifying the effect of losses over the response in the synthesis process, by performing the opposite mathematical operation over (1). In consequence, when the predistorted filter works in the presence of loss a compensation occurs. However, restoring filter Q causes an increase in insertion loss and a degradation of return loss.

Adaptive predistortion is an evolution of classical predistortion in which corrections are weighted by an arbitrary vector v_i obtained by optimizing the filter response. This approach tries to restore filter Q to an effective or desirable quality factor (Q_{eff}) bigger than the Q_u. This approach results in much less insertion and return loss penalty without degrading seriously in-band response linearity.

In order to synthesize a predistorted response it is needed: the filtering functions and singularities from the non-predistorted lossless lowpass prototype filter, the bandpass parameters (f_c and BW), the anticipated Q_u, the desired quality factor (Q_{eff}) and the weight vector ($\mathbf{v}$). In this work we have predistorted a six poles filter with two transmission zeros located at $\omega = \pm 2.2$, centered at $f_c = 13.05$ GHz with $BW = 340$ MHz bandwidth, and $RL = 21$ dB. The desired target quality factor has been set to $Q_{eff} > 15000$.

In order to obtain the anticipated Q_u the rectangular waveguides mode chart is used to choose initial cavity dimensions. Assuming $a = 2b$ and considering silver as material and working mode the fundamental one (TE_{101}), we choose $(a/l)^2 = 0.5$ obtaining an anticipated Q_u of 5177, then $Q_{eff}/Q_u \simeq 3$. The weight vector is chosen to be $\mathbf{v} = [1.5 \quad 1.5 \quad 1.1 \quad 1.1 \quad 0.9 \quad 0.9]$. We calculate the shift factor σ using the formula:

$$\sigma_i = v_i \frac{f_c}{BW}\left(\frac{1}{Q_u} - \frac{1}{Q_{eff}}\right) \text{ with } i = 1, \ldots, N \tag{2}$$

This shift factor is applied to the poles of the filtering function e_k to obtain the predistorted filter poles $e_{kr} = e_k + \sigma$. Shifted poles must comply Hurtwiz's condition so from (2) the maximum achievable Q_{eff} can be computed.

From predistorted poles polynomials $E(s)$ and $P(s)$ that define the predistorsted transfer function $S_{21}(s)$ can be calculated, since transmission zeros p_k remain unchanged. Then, numerator polynomials of the reflection functions $S_{11}(s)$ and $S_{22}(s)$ ($F(s)$ and $F_{22}(s)$ respectively) can be obtained applying the conservation of energy condition and taking paraconjugated pairs of zeros around the imaginary axis. Zeros for the polynomial $F(s)$ are selected one by one arbitrarily, taking one of each pair. The paraconjugated polynomial $F_{22}(s)$ is composed of the remaining zeros, generating the complementary function. There are $2N$ possible combinations of zeros to set up the polynomials. We chose the distribution of reflection zeros maximizing or minimizing μ parameter calculated as:

$$\mu = \left|\sum_{k=1}^{N} Re(f_{kr})\right| \tag{3}$$

,where f_{kr} are the coefficients of the corresponding $F(s)$ polynomial.

The distribution of the reflection zeros sets the symmetry and synchrony of the folded coupling matrix. Supposing that the non-predistorted matrix is synchronous (without frequency offsets) and symmetric (symmetrical realization), if μ is maximized the folded coupling matrix remains synchronous but becomes asymmetrical. On the other hand, if μ is minimized the predistorted folded coupling matrix obtained is maximally symmetric but asynchronous. The later case produces a filter more difficult to tune. Table I shows zeros and poles obtained for the predistorted filter computed from the non-predistorted ones. From them it is possible to obtain the predistorted folded canonical N+2 coupling matrix (see Table II), whose response is shown in Fig. 1. If the effect of loss is included in the lossless prototypes synthesized, an insertion loss of 0.259 dB for the non-predistorted filter and 0.3747 dB for the predistorted one is obtained.

B. Electromagnetic Design

For obtaining the required coupling values of the predistorted coupling matrix in II, four different coupling mechanisms (see Fig. 2a-d) have been characterized using a full-wave EM simulator. Using these characterizations initial dimensions of the overall structure (see Fig. 2e) have been obtained. Final dimensions are obtained from full-wave EM analysis of the complete model and computer aided tuning. This later step takes into account additional interactions (parasitic effects) not considered in coupling mechanisms characterization.

Reflection zeros non-predistorted filter (f_k)	Reflection zeros predistorted filter (f_{kr})	RX/TX poles non-predistorted filter (e_k)	RX/TX poles predistorted filter (e_{kr})
+0.9684j	-0.2210 - 0.2796j	-0.1261 + 1.0923j	-0.1216 + 1.0923j
-0.9684j	0.1414 - 0.7489j	-0.1261 - 1.0923j	-0.1216 - 1.0923j
+0.7206j	-0.1414 + 0.7489j	-0.3717 + 0.8287j	-0.3662 + 0.8287j
-0.7206j	0.2210 + 0.2796j	-0.3717 - 0.8287j	-0.3662 - 0.8287j
+0.2680j	-0.9856j	-0.5433 + 0.3134j	-0.5359 + 0.3134j
-0.2680j	+0.9856j	-0.5433 - 0.3134j	-0.5359 - 0.3134j

TABLE I

ZEROS AND POLES OF THE NON-PREDISTORTED AND PREDISTORTED FILTERS.

	S	1	2	3	4	5	6	L
S	0	1.0128	0	0	0	0	0	0
1	1.0128	0.0438	0.8490	0	0	0	0	0
2	0	0.8490	0.0514	0.6037	0	-0.0525	0	0
3	0	0	0.6037	-0.0777	0.6381	0	0	0
4	0	0	0	0.6381	0.0774	0.6038	0	0
5	0	0	-0.0525	0	0.6038	-0.0518	0.8482	0
6	0	0	0	0	0	0.8482	-0.0431	1.0118
L	0	0	0	0	0	0	1.0118	0

$R_S = 1.0258$	R_L =1.0237

TABLE II

FOLDED CANONICAL N+2 PREDISTORTED LOW PASS COUPLING MATRIX.

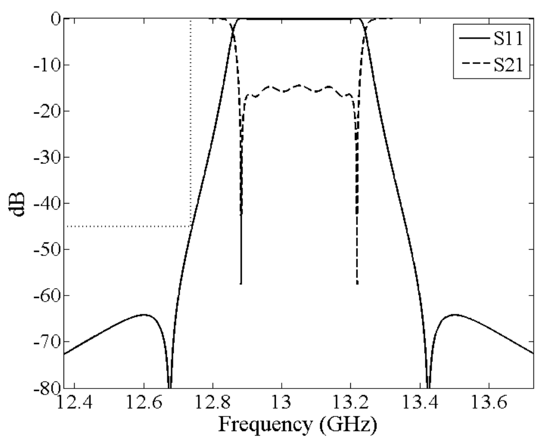

Fig. 1. Theoretical predistorted response.

Fig. 3 shows theoretical response of the non-predistorted filter and the response of the structure in Fig. 2e after tuning it to obtain a non-predistorted response. Fig. 4 shows theoretical response of the predistorted filter and the response of the structure in Fig. 2e after tuning it to obtain a predistorted response. Differences between theoretical and simulated (tuned) responses are due to parasitic couplings and frequency offsets not considered in the synthesis (as it is difficult to know them “a priori”).

III. RESULTS ANALYSIS

Finally, losses are included in the EM model setting aluminium conductivity ($\sigma = 38 \cdot 10^6$ S/m) in all the walls. Fig. 5 clearly shows that predistorted response insertion and return losses are worse in the predistorted filter, but it presents also better insertion loss flatness in the passband.

Table III summarizes the obtained results. In both cases, the Q_u obtained by simulation is lower than the theoretical, and correspondingly insertion losses are also higher. Moreover, the simulated Q_{eff} is lower than the theoretical one. This is due to the fact that we used an adaptive predistortion method.

	Non-predistorted		Predistorted	
	Theo.	Sim.	Theo.	Sim.
IL	0.259	≃0.3	0.3747	≃0.4
Q_u	5177	4595.1	5177	4677.4
Q_{eff}	-	-	15531	11652

TABLE III

SUMMARY TABLE OF RESULTS OBTAINED.

Ku-band predistorted filter shows only 0.1 dB of additional loss with respect to its non-predistorted counterpart. Moreover, adaptive predistortion used here causes just a small degradation of return loss. Depending on the application this performance degradation could be acceptable for input filters, where noise figure will be also affected by the same amount of losses. Additionally, for spurious rejection filters, a more aggressive predistortion could be applied since return loss performance loss could be recovered by means of isolators, and previous LNA amplification would mitigate insertion loss and noise figure increase.

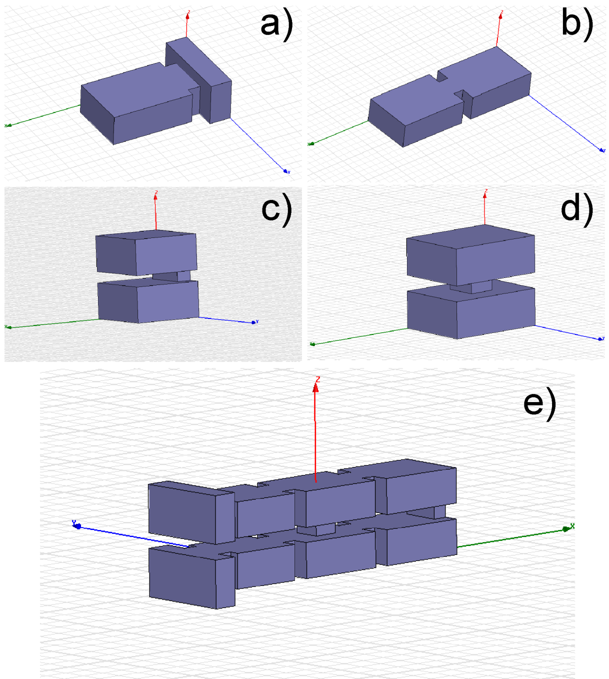

Fig. 2. Full-wave EM models a) external coupling, b) in-line inductive coupling, c) folded inductive coupling, d) capacitive cross-coupling, and e) overall structure.

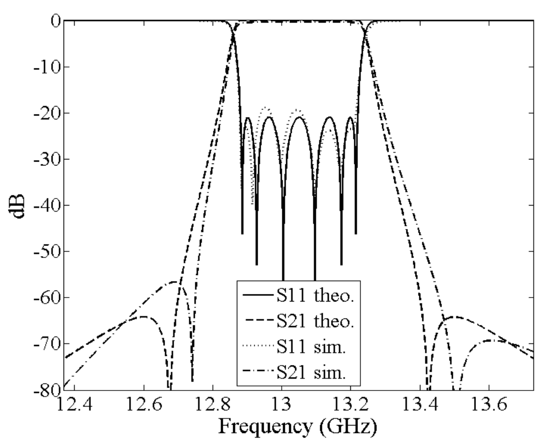

Fig. 3. Theoretical non-predistorted response without considering parasitic couplings (theo) and considering them (real).

IV. Conclusion

In this work an adaptive predistortion synthesis has been applied to the design of a six-pole predistorted rectangular cavities filter with two transmission zeros and folded topology. Responses obtained from full-wave EM simulations of the complete structure show very good agreement with expected theoretical responses. It seems feasible to use this method in order to design high performance ($Q > 10000$) input filters with transmission zeros in standard rectangular waveguide technology.

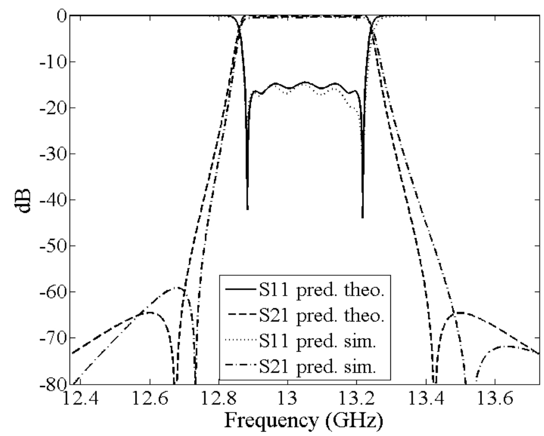

Fig. 4. Theoretical predistorted response without considering parasitic couplings (theo) and considering them (real).

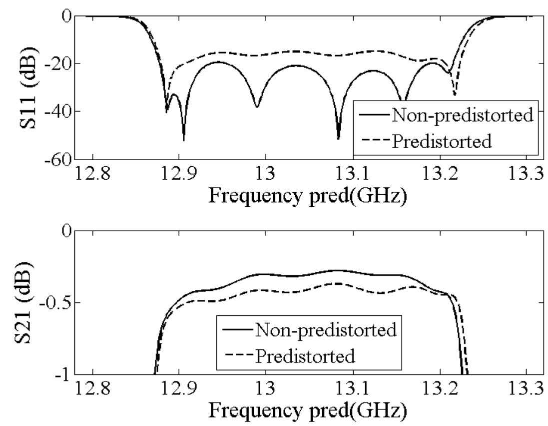

Fig. 5. Comparison between non-predistorted and predistorted responses S_{11} (top) and S_{21} (bottom).

References

[1] G. Maral, M. Bousquet, and Z. Sun, *Satellite communications systems: systems, techniques and technology*. Wiley, 2009.

[2] G. Matthaei, L. Young, and E. Jones, *Microwave filters, impedance-matching networks, and coupling structures*. Artech House Dedham, MA, 1980, vol. 1964.

[3] R. Cameron, "General coupling matrix synthesis methods for chebyshev filtering functions," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 4, p. 433–442, 1999.

[4] A. Atia and A. Williams, "Narrow-bandpass waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. 20, no. 4, p. 258–265, 1972.

[5] L. Accatino, G. Bertin, and M. Mongiardo, "A four-pole dual mode elliptic filter realized in circular cavity without screws," *IEEE Trans. Microwave Theory Tech.*, vol. 44, no. 12, p. 2680–2687, 1996.

[6] A. Williams, W. Bush, and R. Bonetti, "Predistortion techniques for multicoupled resonator filters," *IEEE Trans. Microwave Theory Tech.*, vol. 33, no. 5, p. 402–407, 1985.

[7] M. Yu, W. Tang, A. Malarky, V. Dokas, R. Cameron, and Y. Wang, "Predistortion technique for cross-coupled filters and its application to satellite communication systems," *IEEE Trans. Microwave Theory Tech.*, vol. 51, no. 12, p. 2505–2515, 2003.

[8] M. Yu and V. Miraftab, "Shrinking microwave filters," *Microwave Magazine, IEEE*, vol. 9, no. 5, p. 40–54, 2008.