A UWB *Transformer-C* Orthonormal State Space Band-reject Filter in 0.13 μm CMOS

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***Abstract*— An RF passive orthonormal ladder filter using transformers is presented, where the output is obtained from a linear, weighted combination of the voltages or currents at predetermined nodes or branches. With this topology, arbitrary rational transfer functions can be mapped onto silicon. Key features of this single-input, multiple-output (SIMO) topology include low-pass to band-pass/reject transformation without doubling the order of the filter and the realization of transmission zeros in the right-half-plane (RHP) (for superior approximations). As a proof of concept, a 7^{th} order transformer-C filter implemented in CMOS 0.13 μm technology that can be used as a pulse shaping network (pulse width less than 0.5 ns) or band selection filter (offering a minimum of 20 dB attenuation at the IEEE802.11a WLAN band) for UWB transceivers is presented.**

I. Introduction

Ultra-wideband (UWB) technology is viewed as a potential candidate for wireless short-range data communication in the unlicensed 3.1-10.6 GHz band allocated by the FCC. It promises high data-rate short-range communication at low-cost and low-power consumption due to its capability of sharing the bandwidth resources. One form of UWB communication is impulse radio, where short transient pulses (duration in the order of hundreds of picoseconds) are transmitted, which occupy a bandwidth of a few GHz [1].

As UWB systems transmitting at low spectral densities overlap with the bands of many other existing narrowband systems (e.g., IEEE 802.11a), this wide bandwidth cannot be exclusively assigned to UWB signals. To guarantee peaceful co-existence and to gain acceptance of UWB technology worldwide, interference from narrowband transceivers to UWB transceivers and vice versa must be avoided [2]. For example, the spectrum of a pulse shaping filter must not only adhere to the emissions mask of the UWB communication standard but also provide out-of-band attenuation in order to minimize aggregation. To this end, a band-reject filter can be employed.

In this paper, we demonstrate that *any* rational transfer function can be realized by a passive filter using transformers, where the output of the filter is obtained from a linear, weighted combination of the voltages or currents at predetermined nodes or branches. As a design example, a 7^{th} order filter is chosen with a bandwidth from 3.1-10.6 GHz and a notch at 5.2 GHz offering the best compromise between roll-off, attenuation and hardware complexity. The notch depth complies with the U-NII criteria (notch depth $\geq$ 20 dB @ 5.15-5.25 GHz) to achieve the desired co-existence with WLAN. In order to map the desired transfer function onto a circuit realization, a state-space description is adopted.

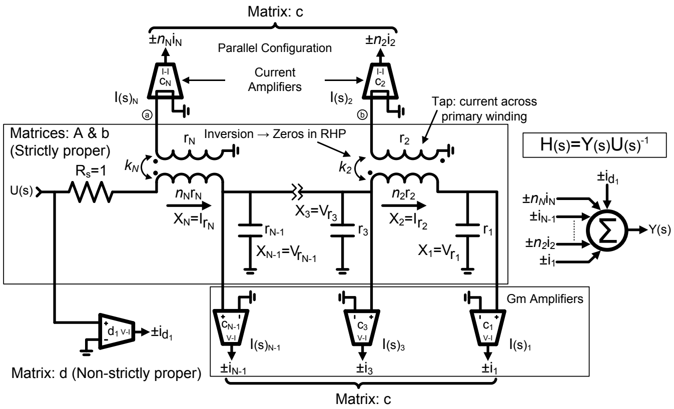

Fig. 1. *Generic orthonormal* transformer-C *state space filter*

II. Orthonormal State Space Filter

The proposed generic active/passive orthonormal ladder filter in Fig. 1 resembles that of a singly terminated low-pass LC ladder network, whose states are defined as the currents through the inductors and the voltages available across the capacitors. Note that the poles (i.e., the roots of denominator $D(s)$) of the filter are positioned in the left-half of the s-plane by the singly terminated *transformer-C* ladder and the zeros (i.e., the roots of numerator $N(s)$) are realized by the output summing stage, which implements the c vector.

To calculate the values of the reactive elements r_i (i.e., $([r_0; r_1, , r_n])$) we apply a continued fraction expansion on $D(s)$. Not only to realize the coefficients of the c matrix but also to compensate for the insertion loss of the filter, transconductance and current amplifiers can be employed to read out the output voltage and currents, respectively. The single element of matrix d is implemented using a transconductor for non-strictly proper (high-pass) transfer functions (i.e., order of $N(s) = D(s)$).

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The salient features of this topology are,

1) Realization of arbitrary rational transfer functions (Butterworth, Elliptic, Chebyshev, InverseChebyshev, etc.)
2) Low-pass to band-pass/reject transformation without doubling the order of the filter
3) Realization of transmission zeros in the right-half-plane (RHP) (not feasible with common RLC ladder structure)
4) Single-input multiple-output (SIMO) topology allows for an output comprising two or more intermediate transfer responses

III. NUMERICAL FILTER APPROXIMATION AND ORTHONORMAL STATE SPACE SYNTHESIS

A filter is usually quantitatively described by its frequency domain magnitude response. The remaining specifications, such as the time domain (i.e., step and impulse) responses, phase and complexity are usually qualitatively defined and frequently neglected. Optimizing the performance characteristics on solely one criterion may result in an undesired performance in another (e.g., better magnitude response may result in a worse time domain response).

Because of fast, cheap computational methods, which effortlessly supply order-based coefficients for a normalized low-pass filter, engineers have become handicapped to a small set (e.g., Butterworth, Elliptic, Chebyshev, InverseChebyshev, Bessel, and a few others) of filter types based on conventional deterministic methods to synthesize a transfer function optimized only in the frequency domain. This results in a vast space of filter coefficients unexplored. We propose a generalized method of filter approximation optimizing both the time and/or frequency domain responses (see Fig. 2).

One of the most important aspects of analog filter synthesis is that the approximating transfer function or data set must lead to a physically realizable network which is dynamically stable. To achieve a good approximation to a given function $f(x)$ that is continuous in a given interval $a \leq x \leq b$, by some polynomial $g(x)$, there exist several mathematical techniques (e.g., *MiniMax*, Chebyshev Knots, Padé, Taylor, Splines, etc.) that are frequently used. An approximation that has proven to

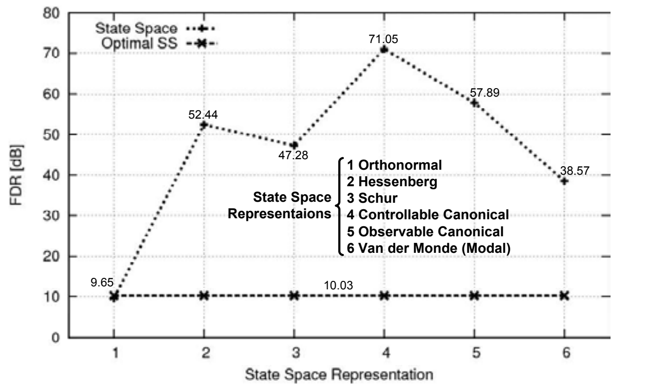

Fig. 3. *FDR comparison for different state-space descriptions of a 7^{th} Daubechies' scaling function*

be successful for synthesizing arbitrary transfer functions and impulse responses is the Padé approximation of the Laplace transformed impulse response of the filter. By substituting $j\omega$ for s, the frequency domain characteristics are obtained and thus can be optimized, as the Laplace transform has a one-to-one mapping to the frequency domain.

Among the many possible state space descriptions for a transfer function, the orthonormal ladder form stands out, as it is semi-optimized for dynamic range (i.e., approximately 2 dB inferior to a fully optimized representation) [3] and thereby least sensitive with respect to mismatch and component variations [4]. In order to maximize the dynamic range of the system, one should minimize the objective functional (FDR), which represents the relative improvement of the dynamic range and contains all parameters which are subject to manipulation by the designer. The FDR comparison for different state-space descriptions of a 7^{th} order Daubechies' scaling function is given in Fig. 3 [5].

Once the state space description (i.e., matrices A-D, where A is the state matrix, B is the input matrix, C is the output matrix and D is the feedforward matrix) of the desired transfer function is formulated, it can then be mapped onto a lumped element ladder structure.

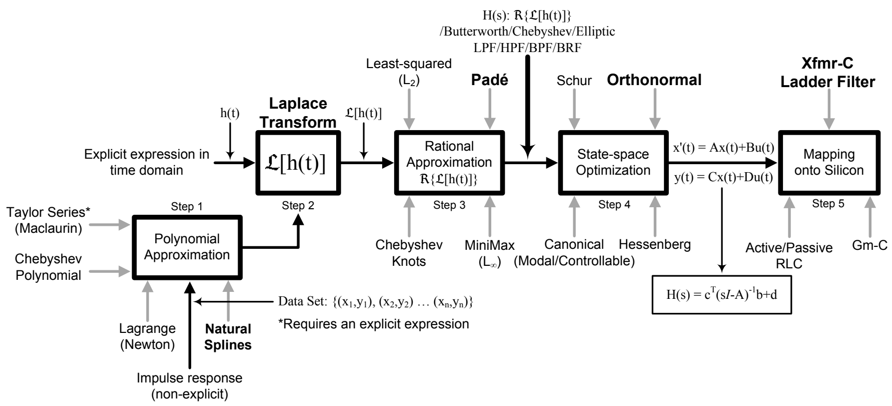

Fig. 2. *Analog filter synthesis*

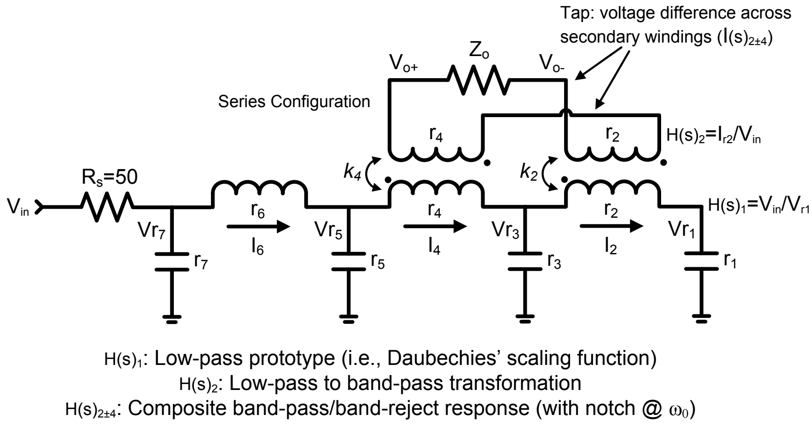

Fig. 4. 7^{th} *order orthonormal* transformer-C *state space band-reject filter*

IV. 7^{th} Order Orthonormal State Space Band-reject Filter

The actual design of the 7^{th} order *transformer-C* band-reject filter to be implemented in CMOS technology is depicted in Fig. 4, where k and r_n denote the coupling coefficient of the transformers and the component reactances, respectively. The voltage across the capacitors and the current through the inductors or the primary windings of the transformers are given by V_n and I_n, respectively. The intermediate transfer functions are denoted by $H(s)_n$.

By taking the voltage difference of the secondary windings of transformers X_2 and X_4 and through proper component scaling (by their turns ratio (n) and coupling coefficient (k)), a low-pass to band-pass/band-reject transformation of a strictly proper (i.e., order of $N(s) < D(s)$) transfer function is realized. Upon calculating the input impedance, Z_{r7_1},

$$Z_{r7_1} = ((((((r_1 + r_2) \parallel r_3) + r_4) \parallel r_5) + r_6) \parallel r_7)$$

and (in our case, low-pass response) $H(s)_1$, any intermediate transfer function can be derived. The output of the proposed filter is a composite of two intermediate, band limited transfer responses resulting in a notch in the pass-band as given by the overall transfer function $((H(s)_5 - H(s)_3)/r_4) + ((H(s)_3 - H(s)_1)/r_2)$.

Process variations and mismatch will cause the notch to deviate from the desired frequency (ω_0). For frequency tuning, only the source and capacitive impedances can be scaled. First, in order to scale the source impedance to R and change the frequency of the notch from the normalized frequency ω_n to ω_0, we use the transformations, $L'_n = L_n R \omega_0$ and $C'_n = \frac{C_n}{R}\omega_0$ on the impedances of the lumped elements. Then, for frequency tuning of the notch, varactors can be employed instead of capacitors. The transformations now become, $R^T = \frac{R}{\alpha}$, $L'_n = L_n$ and $C'_n = \frac{C_n}{\alpha^2}$, where the frequency scaling factor $\alpha = \frac{\omega_0}{\omega_c}$ $(c = 1, 2, \ldots, \aleph)$ with ω_c being the compensation frequency. Finally, for amplitude correction, current amplifiers can be employed at the output stage to compensate for any insertion loss in the pass-band.

V. Measurement Results

Fig. 5 and Fig. 6 show the simulated and measured magnitude and phase response of the orthonormal *transformer-C* state-space filter realized in 0.13 μm CMOS IC technology. The desired U-NII co-existence criteria is satisfied, even though a 3 dB reduction in notch depth and a frequency shift of 100 MHz is observed. Measurements show a sharper roll-off at higher frequencies than required by the FCC frequency mask. Moreover, the insertion loss across the pass-band is inversely proportional to the notch depth, for both the band-stop filter of Daido Steel (i.e., fabricated using LTCC technology) and the CMOS based transformer-C state space filter.

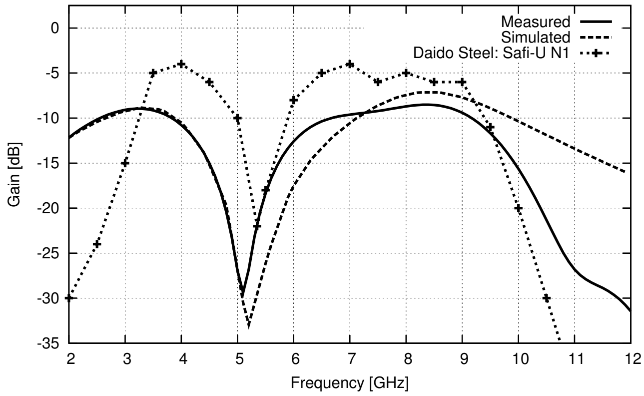

Fig. 5. *Magnitude response of the* 7^{th} *order orthonormal* transformer-C *state space band-reject filter (without de-embedding)*

As a result, in the time domain, the measured and simulated impulse responses of the filter vary by a fraction of a nanosecond (see Fig. 7). Overall, the simulated results accurately predict the actual behavior of the proposed filter topology, as can be deduced from the measured data.

The chip microphotograph of the *transformer-C* band-reject filter is shown in Fig. 8. The key elements of this circuit are two high performance on-chip passive multi-layer stacked transformers that act as the voltage-difference sensing elements.

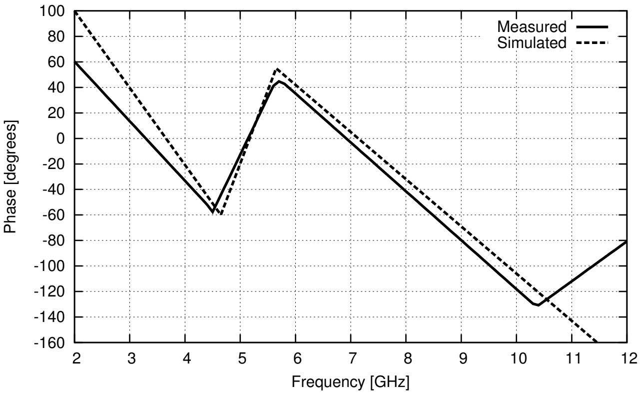

Fig. 6. *Phase response of the band-reject filter*

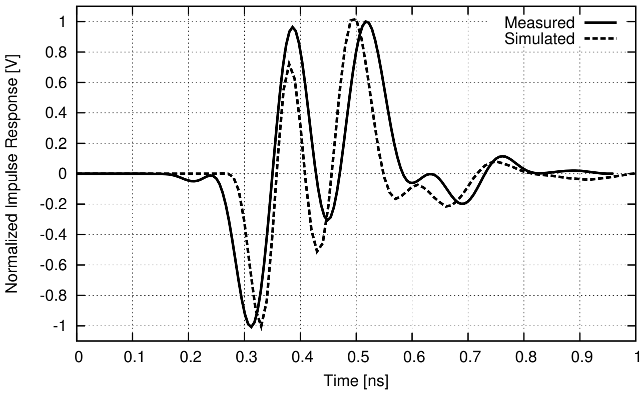

Fig. 7. *Impulse response of the band-reject filter*

Each transformer has 3.5 turns, metal width of 10 μm, coil spacing of 5 μm, inner dimension of 80 x 90 μm^2, an overall dimension of 150 x 150 μm^2 and a coupling coefficient of 0.75. The specifications of the 7^{th} order orthonormal *transformer-C* band-reject filter are highlighted in Table I.

The interconnect length of the bond wire is about 500 μm, resulting in a series inductance to the RF input/output

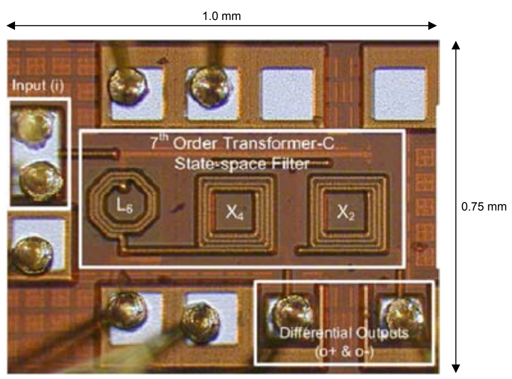

Fig. 8. *Chip microphotograph of the* 7^{th} *order orthonormal* transformer-C *state-space filter in 0.13* μm *CMOS technology; active area is 0.15 mm*^{2}*; physical dimensions are (0.625 x 0.25) mm*

TABLE I

***TRANSFORMER-C* FILTER SPECIFICATIONS**

Parameter	Simulated	Measured
Filter Type	Band-reject	
Order	7 (1-IND; 2-XFMR; 4-MIMCAP)	
Reactance Values (R_s =50 Ω)	r7=300; r5=825; r3=900; r1=350; (fF) r6=1; r4=2.2; r2=2.2; (nH)	
Insertion Loss	-8 (LB), -7.5 (UB) dB	-9 (LB), -8 (UB) dB
Bandwidth	(FCC Emissions Mask → ~ 3.1-10.6 GHz)	
Lower-band (LB)	2.5-4.5 GHz	2-4 GHz
Upper-band (UB)	7-10 GHz	6-9.5 GHz
Pulse width	≤ 0.5 ns (10-90 %)	
Notch	(U-NII Criteria → ≥ 20 dB @ 5.2 GHz)	
Depth	25 dB	22 dB
Frequency	5.2 GHz	5.10 GHz
Transformers (X_2/X_4) Dimensions	Turns ratio (n) ~ 1; Coupling coefficient (k): 0.75; 150 x 150 μm^2	
Termination		
Input	Single-ended (50 Ω)	
Output	Differential (100 Ω)	
Physical size		
Chip Area (LxW)	(1.0 x 0.75) mm; 0.75 mm2	
Active Area (LxW)	(0.625 x 0.25) mm; 0.156 mm2	
Technology	0.13 μm CMOS IBM	

of approximately 0.5 nH. Finally, to guarantee that parasitic behavior does not influence the performance of the filter, at its input, multiple gold ball wire bond interconnects were placed in parallel during packaging.

VI. CONCLUSIONS

The proposed *transformer-C* filter methodology allows for the realization of (any) arbitrary rational transfer onto silicon. As a design example, a 7^{th} order *transformer-C* orthonormal state-space band-reject filter in CMOS 0.13 μm technology is presented. Characteristics such as low-pass to band-pass/band-reject transformation without increasing the order of the filter, the realization of transmission zeros in the right-half-plane and the use of transformers, which allow for the weighted combination of the intermediate transfer functions are demonstrated with this topology.

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