

Absorptive Near-Gaussian Low Pass Filter Design with Applications in the Time and Frequency Domain

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Abstract — The work presented here is for the design of an absorptive low pass filter for use in the time and frequency domain. The filter presented is absorptive in the stop band, flat in group delay to twice the half power frequency and near-gaussian in shape. The design of the low pass filter is general with design examples in microstrip and coplanar waveguide at 40GHz. Frequency domain measurements to 110GHz and time domain measurements at 40Gbits/s are presented. The absorptive filter presented has uses in pulse shaping, rise time alteration and harmonic matching.

Index Terms — 40Gbit/s, time domain, absorptive, low-pass, rise-time, gaussian.

I. INTRODUCTION

Time domain systems often contain significant energy beyond the relation of the bandwidth to the rise time, $f_{BW} = 0.35/t_r$ [1]. A 75GHz spectrum analyzer measurement of the output of a data amplifier exhibiting an 8.5 ps risetime (10-90%) with a 43Gb/s $2^{31} - 1$ PRBS input signal is shown in Fig. (1), where it is compared to the power spectrum of an ideal 43 Gb/s $2^{31} - 1$ PRBS having risetime of 0 pS. It can be seen that the measured PRBS power spectrum follows closely an ideal sinc^2 function [2] for a pseudo-random non-return-to-zero bit sequence (PRBS) of $2^{31} - 1$. The reduced magnitude of the higher frequencies is related to the finite risetime of the output signal. At 60GHz an 8.5ps risetime signal should have a power spectrum magnitude 6.7dB below an ideal sinc^2 function according to the gaussian relation. Comparison of the ideal vs. measured response at 60GHz demonstrates a reasonable agreement within 2dB.

The prior approximation depends heavily on the assumption that the high frequencies have frequency rolloff characteristics gaussian in nature. In reality, higher frequencies in amplifiers have non-idealities such as dispersion and undesirable second harmonics that cause the pulse shape to be distorted.

Pulse shaping by limiting the rise time and bandwidth can be accomplished by simply low pass filtering the output. Traditional frequency domain filters such as Chebyshev and Butterworth have inherently poor group

delay characteristics that cause jitter in the time domain by delaying parts of the high frequency data with respect to low frequency. The dispersive nature of these filters inject a significant amount of jitter onto a time domain signal. Bessel-Thompson or maximally flat group delay filters presented in [5] and [6] have been successful in some applications due to the excellent group delay characteristics. However, the maximally-flat filters are reflective in the stopband.

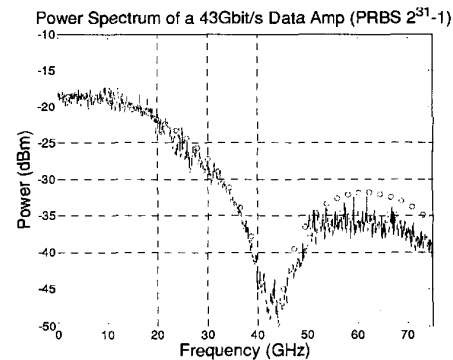


Fig. 1. Power spectrum of a 43Gbit/s data amplifier (solid line) as compared to ideal PRBS sinc function (circles).

A mismatched amplifier driving a reflective filter can result in multiple reflections that may be a major source of jitter. Ideally, a time domain low pass filter should have rolloff characteristics that are gaussian in nature (to eliminate any over or undershoot), flat group delay and absorptive rather than reflective in the stopband. This was first presented as a proprietary constant Z filter in [3] and a derivation an elemental version of this filter was presented recently in [4]. The low pass filter design presented here has the identical RLC topology presented in [4] but with a simplified derivation and additional analysis of the performance.

The gaussian absorptive low pass filter also has important applications in the frequency domain. Often frequency doublers and mixers perform optimally when

provided with an appropriate termination impedance for all harmonics. In high performance systems this may be accomplished using an attenuator followed by a filter to remove spurs and harmonics. Using an absorptive low pass filter of the appropriate order and cutoff frequency, higher harmonics can be terminated and attenuated while allowing the desired signal to pass through.

Self oscillation that occurs in amplifiers when higher harmonics are terminated improperly can be eliminated by designing an absorptive low pass filter directly onto the IC substrate. Oscillators may benefit by similarly absorbing higher order harmonics.

This design creates an invaluable simulation filter as well. The authors have used this filter to create a near-ideal source with adjustable risetime in a simulation template in order to do accurate system analysis on time domain designs.

II. FILTER TOPOLOGY AND PROTOTYPE DESIGN

The implementation of a Gaussian low pass filter begins with the properties of a lossy transmission line. A lossy transmission line has flat group delay, maintains proper port match and attenuates the high frequencies. Differentiating itself from other filters, the transmission line as a filter simply absorbs, rather than reflects, unwanted high frequencies.

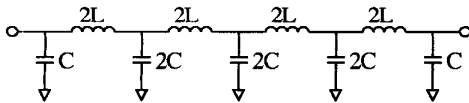


Fig. 2. Lumped element transmission line.

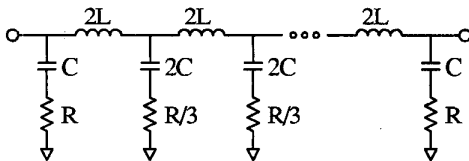


Fig. 3. Lumped element transmission line with lossy element included. Note series rather than parallel placement of the resistor.

The design of the absorptive filter begins with the lossless lumped element artificial transmission line described in many texts such as [5]. A diagram of a lossless lumped element line is shown in Fig. (2). The inductance and capacitance values are calculated by Eqn 1 for a given characteristic impedance Z_0 . Dielectric loss is often taken into account by a resistor in parallel with the shunt capacitance. This is valid for only one frequency. Introduction of a resistor in series rather than parallel

results in a transmission line where loss increases with frequency. At low frequencies the transmission loss is only from the DC loss of the series inductors. At very high frequencies the inductors are open and the capacitors are short circuited and the impedance is R . The transition impedance between low and high frequencies is set to a critically damped value by Eqn. (1) as described in a circuit textbook [8]. This critically damped ratio is what determines the gaussian response of the filter.

$$Z_0 = \sqrt{\frac{L}{C}} = R \quad (1)$$

$$\omega_0 = \frac{1}{\sqrt{LC(n-1)}} \quad (2)$$

$$C = \frac{1}{\omega_0 Z_0 \sqrt{n-1}} \quad (3)$$

$$L = Z_0^2 C \quad (4)$$

The -3dB frequency is set by the simple relation in Eqn. (2), which is slightly modified to include the number of elements n . It should be noted here that an n -element filter creates an $N=n+1$ order filter due to the effect of the additional resistance. This was determined by derivation of the filter transfer function. The unique values of C and L are determined by Eqn. (3) and (4) through substitution.

A cascaded pi-network of CLC would yield a value of $Z/2$ for R but empirically a value of $R/3$ provided better match and improved group delay. A more rigorous analysis in [4] came to the same conclusion analytically. By adjusting the internal R value, the group delay flatness and rolloff characteristics can be optimized for a given application.

Fig. (4) – (6) are normalized plots of the performance of the absorptive filter for $N=4$ to 14. All N are even such that the filter is always symmetrical (odd number of n -elements). Fig. (4) shows that for $N=6$ to $N=14$ the filter is nearly gaussian to twice the half power frequency. Stopband performance is improved for higher orders. Fig. (5) demonstrates the match performance as compared to both order and against a 3rd order butterworth and 10th order maximally flat group delay filter calculated from [6]. Match is improved with increasing N . Fig. (6) shows the group delay performance as a function of N .

III. EXPERIMENTAL RESULTS

Tenth order filters with a 40 GHz 3dB cutoff frequency were created in both coplanar waveguide and microstrip to demonstrate the effectiveness of this design for pulse shaping at 40Gbit/s .

The coplanar waveguide (CPW) circuit was created on a sapphire substrate for it's high dielectric constant and negligible dielectric loss. Inductance was calculated using a length of 95 ohm transmission line. The capacitance was calculated from the gap between a small metal square coupling to the coplanar RF trace. A photograph of the fabricated circuit is shown in Fig. (7).

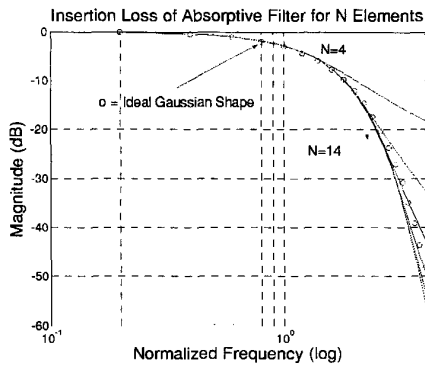


Fig. 4. Magnitude S21 response of absorptive filter.

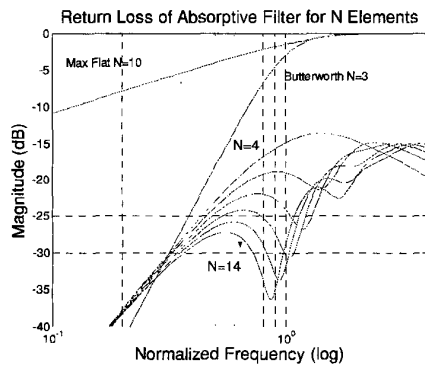


Fig. 5. Return loss S11 of absorptive filter with Butterworth and maximally flat group delay filters for comparison.

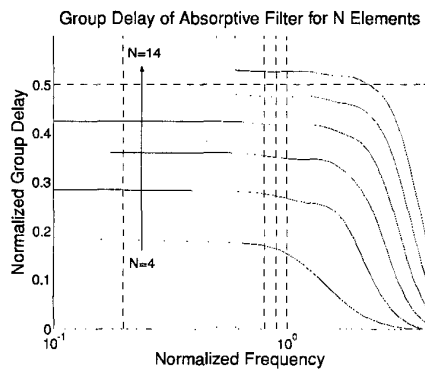


Fig. 6. Group delay performance of absorptive filter for N.

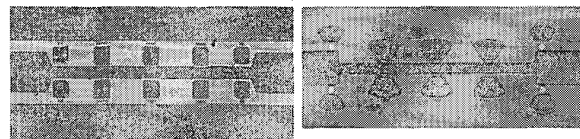


Fig. 7. Fabricated 40GHz absorptive low pass filter in coplanar waveguide (left) and microstrip (right).

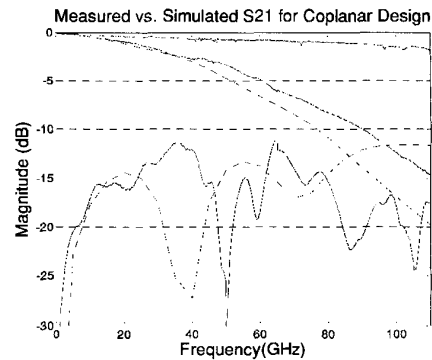


Fig. 8. Measured and simulated results for the 40GHz absorptive coplanar filter design.

The coplanar circuit was mounted in a test package that used 1mm coaxial connectors for broadband measurements to 110GHz. The test package S21 thru line performance is shown with the measured results in Fig. (9). The package has better than -20dB return loss to 110GHz. The filter simulation was done as a full 3D simulation using HFSS. The HFSS simulation neglected the launch from coaxial to CPW. The likely difference in magnitude between simulation and measurement is due to the reduced isolation from the proximity of the coaxial connectors. This is apparent in the reduced stopband performance above 80GHz.

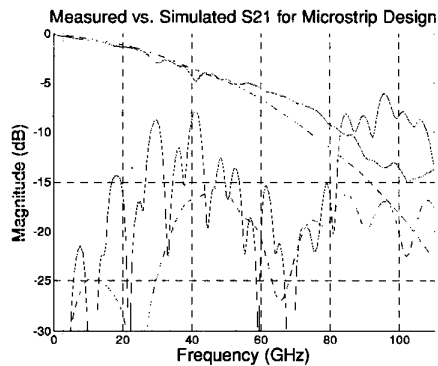


Fig. 9. Measured vs. simulated performance of a 40GHz absorptive microstrip filter.

The microstrip absorptive filter was designed in the same medium except radial stubs were used for the capacitive element. The same 1mm package was used but the coaxial to microstrip launch had not yet been optimized and so severe reflections had a significant effect on the measurement. The general trend of modeled and measured data can be seen in Fig. (9) and (10). Fig. (10) shows that the coplanar circuit, consistent with planar technology theory, offers better dispersive properties and has a flatter group delay than the microstrip equivalent.

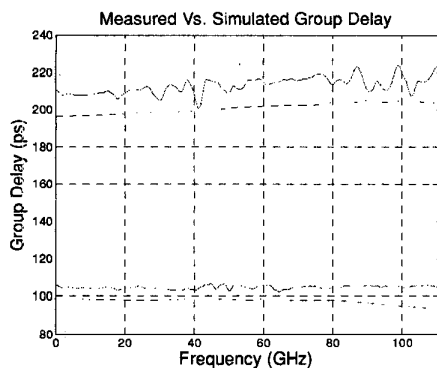


Fig. 10. Measured vs. simulated group delay performance for coplanar and microstrip absorptive low pass filter designs.

Fig. (11) shows a data amplifier PRBS sequence at 40.25Gbit/s before and after an absorptive filter is placed at the output. It is demonstrated here that the overshoot is virtually eliminated while degrading the rise time slightly with only 60fs of additive jitter.

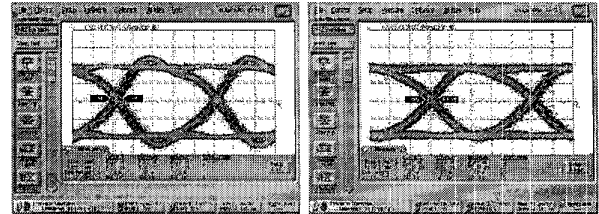


Fig. 11. Time domain measurement of a 40.25Gbit/s data amplifier before and after a 40GHz absorptive low pass filter was placed at the output.

IV. CONCLUSION

An absorptive, near-gaussian low pass filter has been presented that is general and scaleable in frequency and impedance. The measurements have demonstrated excellent results for time domain applications in pulse shaping or rise time alteration. Applications in the frequency domain for harmonic matching and amplifier oscillation suppression are currently being explored. Absorptive bandpass filters have been fabricated using lumped elements and designed using the low pass to band pass transformation demonstrated in [6] with promising results.

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