11.424 GHZ STRIPLINE TRANSVERSAL FILTER FOR SUB-PICOSECOND BUNCH TIMING MEASUREMENTS*

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Abstract

Measurement of time-of-arrival or instantaneous longitudinal position is a fundamental beam diagnostic. We present results from a stripline transversal periodic coupler structure which forms the heart of a sub-ps beam timing detector. This filter structure approximates a sinx/x response in the frequency domain which corresponds to a limited pulse length response in the time domain. These techniques have been used extensively in beam feedback systems at 3 GHz center frequencies with operational single-shot resolutions of 200 fs [1]. We present a new design, based on a 11.424 GHz center frequency, which is intended to offer a factor of four improvement in time resolution. Two-dimensional electromagnetic simulation results are shown, and the design optimization approach leading to the final circuit implementation is illustrated. The prototype circuit has been fabricated on 64mil Rogers 4003 and lab frequency domain and time domain data are compared to the 2-D simulation results. Performance of the prototype circuit is shown with applicability to sub-ps beam measurements in LINAC and FEL applications.

INTRODUCTION

In this paper, we discuss the general application of using these transversal filters for longitudinal position and phase detection in comparison to other potential schemes, followed by a brief discussion of why increasing the frequency could potentially increase the resolution, we then move on to details regarding the design of the filter and discussion of simulated vs. Measurement results. We finally discuss a demo phase detection system we simulated and have preliminarily built and close with conclusions and potential follow on work.

Application

Techniques to measure time-of-arrival or relative phase of a particle bunch are fundamental diagnostics. A bunch can be detected from the signals it generates in pick-up devices, though direct measurements in the time domain can be limited in time resolution due to the difficultly of processing very wideband signals. Some techniques use the bunch passing to resonate a high-frequency resonator as part of the beam vacuum structure, or an external resonator driven from a wideband BPM. This resonator can be a high frequency (GHz), and a phase detection technique can give high resolution in the measurement of the arrival phase. These external resonator techniques [2], [3] require adequate separation of bunches so that the excitation can decay away before the next measurement (a high-Q resonator also offers a narrower measurement bandwidth which can help improve resolution). Another approach samples the beam signals in an electro-optic sampler, which allows very high-resolution time measurements [4], [5]. However this approach is limited to sampling rates of the sampling mode-locked laser, which is typically in the 100 MHz range.

For measurements of closely spaced bunches, these resonator or electro-optic techniques are not useful (for example in bunch-by-bunch longitudinal feedback systems sampling at 500 MHz rates). For these measurement needs, a technique using short periodic coupled microwave circuits was developed [6]. The heart of this technique is a microwave circuit with a sin(x)/x frequency response, so that in the time domain the excited signal has a rect(t) envelope, and ends cleanly after a few cycles of a defined frequency. Systems of this sort have been developed at 1 - 3 GHz in several applications with resolutions of 160 - 200 fs [1]. This paper extends the technique to 11.424 GHz, and potentially improves the measurement resolution by a factor of 4.

Higher Resolution

As timing requirements become more and more stringent for various accelerator facilities, the resolution requirements for timing detection systems continue to increase. It follows logically that to detect finer and finer time scales (sub-ps), the bandwidths and frequencies of the detection electronics need to increase.

The idea for extending this technique to higher frequencies comes from the fact that if we do phase comparisons at X-Band instead of S-Band, we should see a four times increase in phase sensitivity by comparing to a frequency 4 times previous. In the case of the PEP-II longitudinal feedback system receiver noise analysis shows an effective resolution of 200 fs at 2856 MHz [6]. Extrapolation to 11.424 GHz could imply resolutions on the order of 50 fs.

In the real world, things simply don't scale quite so easily, so the authors set out to begin work on an actual demonstration system which could potentially show the aforementioned resolutions. The first step in the process is to design the transversal filter. At this stage, we are still working on the estimation of the actual resolution.

TRANSVERSAL FILTER DESIGN

General Considerations

The basic structure of this filter is that of microwave couplers connected together by quarter wave transmission

lines. A plot showing how the filter shape changes based upon the number of sections is shown in figure 1.
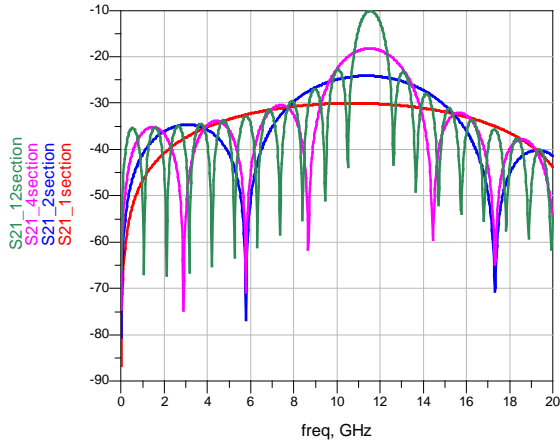

Figure 1: Plots of various numbers of sections of transversal filter

As with any design, it is important to start with design goals and key parameters. The key deign parameters for the filter we designed are shown in Table 1.

Table 1: Filter Design Parameters

Parameter	Value
Number of Taps	12
Center Frequency	11.424 GHz
Board Thickness	64 mils
Board Material	Rogers 4003
Technology	stipline
Coupling per section	30 dB

12 taps were chosen so that the effective output pulse would have a length of approximately 1 ns at a center frequency of 11.424 GHz. The center frequency of 11.424 GHz was chosen because it is a convenient multiple of the 2856 MHz which is main line frequency at the SLAC linac. A board thickness was chosen at 64 mils because on the Rogers material, the line thicknesses were quite well matched to the available stripline launches. The Rogers board material was chosen because it has been shown to work quite well at these frequencies in numerous other projects. Stripline was chosen over microstrip due to its inherent shielding.

In choosing the coupling factor, the design trades-off several constraints. A very low coupling factor is undesirable in the total output signal, but is useful in that the energy removed along the line is a small fraction of the incident pulse, and the coupling does not have to be varied down the line to have constant output pulse amplitude vs. time. Additionally, a strongly coupled line means that small mismatches and imperfections between the sections are more significant in their impact in the time structure of the output pulse. We have experience

building these stripline generators at 3 GHz with coupling factors from 10 through 40 dB, and based on our experience at 3 GHz we chose 30 dB as a reasonable starting point for this 11.424 GHz evaluation.

Detailed Design

To begin the design, rather than just simulate the entire 12 coupler filter, we simulate a single section a single set of connecting lines. The main goal of this is to set the overall through path length to 180 electrical degrees while centering the coupled section at the desired center frequency. This would be seemingly easy since the coupled section, when centered, is naturally 90 degrees long. Then it would just be a matter of adding a 90 degree transmission line to connect to the next coupled section. Unfortunately, you cannot just connect to the next section with a straight line or you will end up with two staggered couplers which are not what we desire. In essence, you want a coupled section followed by a non coupled section. One way to do this would be to offset the connecting lines from the coupler so that they form a coupled section with less coupling. An idea like this is shown in Figure 2

Figure 2: Potential idea for offset connecting lines.

Unfortunately, this did not work well because of the discontinuity between the two lines resulted in a large VSWR. Since we are connecting multiple sections together, the VSWR between sections can become so significant as to render the structure. The structure finally used in the design is as shown in Figure 3.
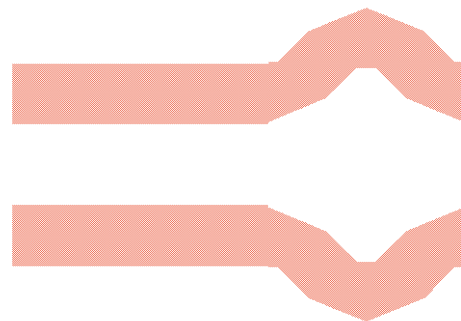

Figure 3: Realized coupler and connecting lines

The Agilent Analog Design System (ADS) used to simulate these structures has two main components useful for this type of design. One uses a model based circuit type simulator for a starting point in the design. While

these models are typically very good, as designs are pushed higher in frequency, it becomes necessary to use the momentum 2.5D field solver which has shown excellent accuracy in the past. Once the single section has been fully optimized so that good return loss and proper phase delay and coupling is achieved then the overall circuit can be combined into the 12 section filter design.

In much the same way as the single section, the twelve section filter is analyzed using a combination of the linear modelling simulation and momentum 2.5D simulations. Because the single section was so well analyzed before the combining, very little iteration was required. A 3D visualization of the circuit as simulated is shown in Figure 4.
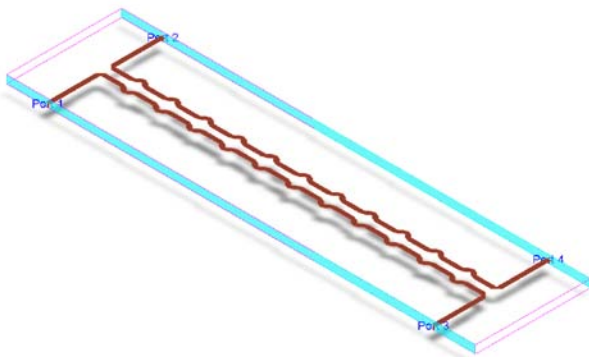

Figure 4: 3D visualization of final 12 coupler filter.

For illustrative purposes, a plot showing the difference between the model based and field solver based solutions is shown in figure 5.
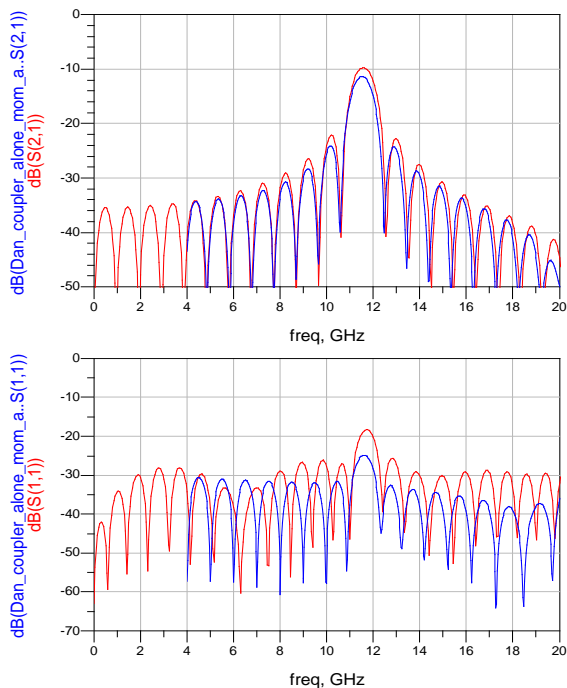

Figure 5: Difference between model and field solver simulations. These differences can be mostly attributed to small errors of the model based simulation. In addition,

coupling in the "non-coupled" sections is ignored in the model based simulation.

FABRICATION AND MEASUREMENT RESULTS

Fabrication

The circuit was fabricated on Rogers 4003 material in two halves to allow for easy attachment of input and output connectors. This immediately introduces some error into the overall design since a small gap of air dielectric could be present between the two halves of the board due to the thickness of the circuit metallization. We chose to ignore this in the original design.

Figure 6 shows a photograph of the board as fabricated. In addition to the board, two gold plated aluminium plates were fabricated to ensure that the boards were held tightly together and to create a stable mount point for the sma stripline launch connectors.

Figure 6: Fabricated board and plates with sma connectors

Measurement

The filters were measured on an Agilent 8720 network analyzer to verify the performance against the simulations. Figure 7 shows the measured response of the filter contrasted with the momentum simulation results. As is clearly seen in this plot there is a frequency error of the center frequency of the filter of about 466 MHz or 4%. This is not a surprise to author DVW, and what is typically done is another turn is done with a new design centered 4% lower in frequency. One revision on the board is usually enough to resolve this type of error. The good news is that the circuit will still behave as expected but with a slightly different frequency of operation. With the 1 ns pulse length, the impact of this 466 MHz error is to introduce a tilt in the phase detected baseband pulse output (instead of mixing the signal to DC, the phase error is really the difference frequency at 466 MHz). Since

each pulse starts off as a unique impulse signal, if the phase detector is set to sine-like detection (nominally zero output) the error signal follows a cosine-like amplitude, and the initial error voltage starts to assume a cosine at 466 MHz For a 1 ns length pulse, for tilts of less than 50% (cosine of 60 degrees) the frequency error should be less than 170 Mhz. The actual measured phase error from sampling this pulse is related to the sampling time jitter and the slope of the output baseband pulse.
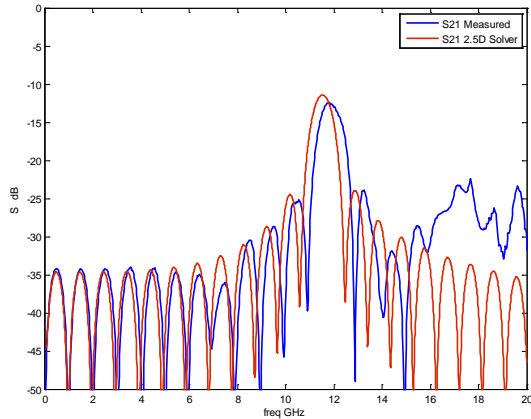
Figure 7: Measured S21 of measured and simulated filter

Testing the circuit in the time domain requires an "impulse" or delta function signal generator. In actual practice, signals from bunched beams serve as excellent impulse generators, and lab generators often have slower rise times and are not as clean. It is possible to test the generator with step-recovery diodes, which produce 100 - 200 ps impulses, though they have shapes which are not Gaussian, and the signals have significant "tail" components after the initial impulse. These generators have served to test our 3 GHz generators, but we observed strange responses using them to excite this 11.424 GHz circuit.

For our initial measurements we injected an approximately 120 ps wide impulse signal generated by a 119 MHz driven step recovery diode. The response was measured using an Agilent 86108 Precision Waveform Analyzer. The obtained response was very surprising to us and led us to return to simulation to see if what we were seeing made sense in comparison to what we actually measured. To do this, we used the time domain SPICE based simulator built into ADS which allows us to combine S-parameter data into a time domain simulation. We used the S-parameter data from the 2.5D solver and for an input as shown in figure 8, we obtained an output as shown in figure 9. Both figures 8 and 9 show the simulated and measured responses. The surprise we observed was the very large spikes at the beginning and end of the pulse train, and the relatively insignificant signal we were seeing at the desired frequency.
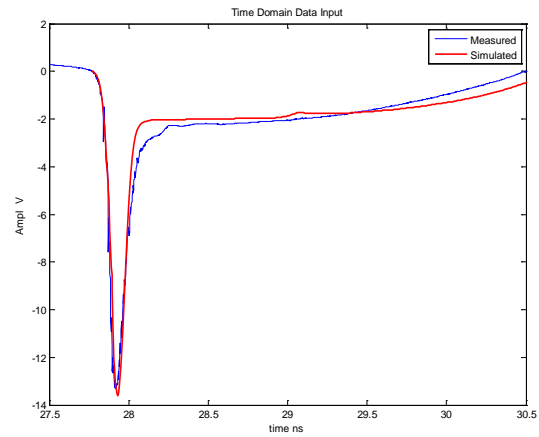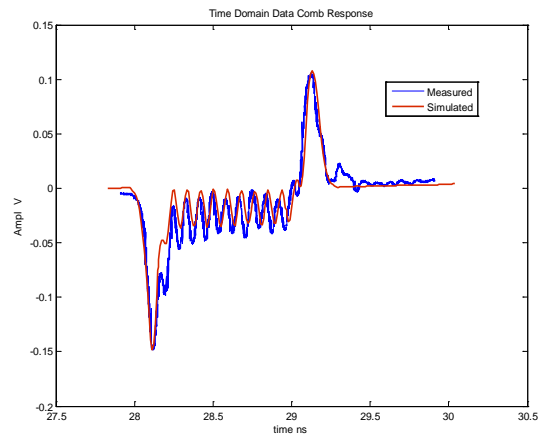

Figure8: Simulated and measured input impulse

Figure 9: Simulated and measured filter time domain response to 120 ps impulse

Upon further investigation in the simulation, we began to realize that the width of the impulse has a profound impact on the "overshoot" at either end of the response. We were able to use a picoseconds pulse labs 3500C 60 ps impulse generator to further verify this and the results from that measurement are shown in Figure 10.
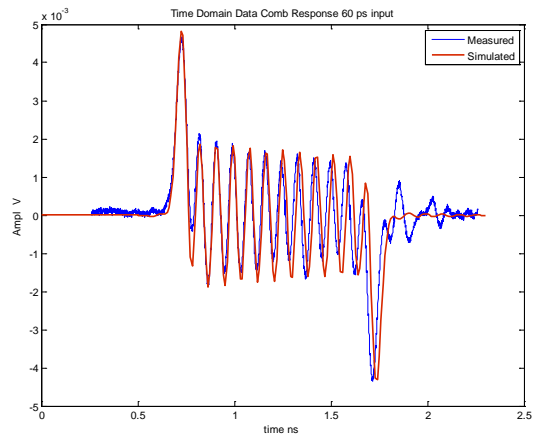

Figure 10: 60 ps impulse response

As a further investigation into this phenomenon, we simulated the ideal circuit using SPICE over a wide range of pulse widths and calculated the "% overshoot" using

the difference of heights between the first overshot impulse and the amplitude of the next peak divided by the amplitude of the first peak. These results are shown in figure 11.
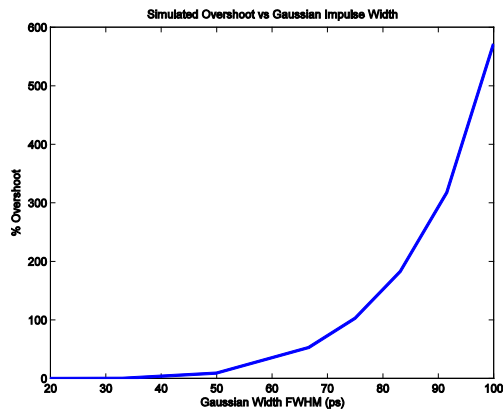

Figure 11: % Overshoot vs. Gaussian impulse width at FWHM

PHASE DETECTION EXAMPLE

As a way to demonstrate this technique, a simple phase detection scheme was simulated and built using our filter. The essential idea is to generate impulses at some sub-multiple of the center frequency of the filter and then use a mixer and low pass Bessel filter to detect the "DC" component of the phase detection. Figure 12 shows the simulation block diagram which is very similar to the actual circuit we built and tested. This type of phase detector has a sinusoidal output vs. Phase shift and the simulation shows this clearly. The system we build contained a variable phase shifter which allowed us to vary the LO phase (unlike what is shown in the simulation diagram).
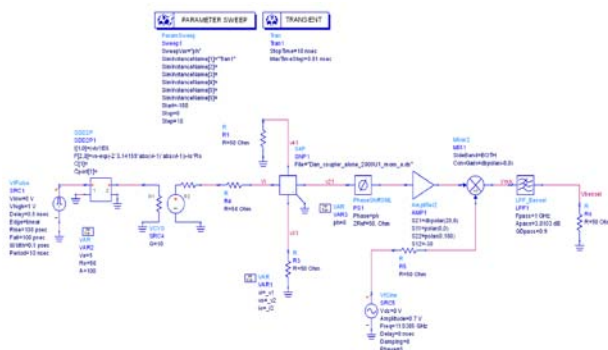

Figure 12: Simple phase detection scheme

We obtained screen captures from the phase detection hardware but were having trouble maintaining constant phase due to variations in temperature. The results from those measurements are shown in Figure 13. A strange asymmetry is occurring; at this point we have not yet had time to fully explain.

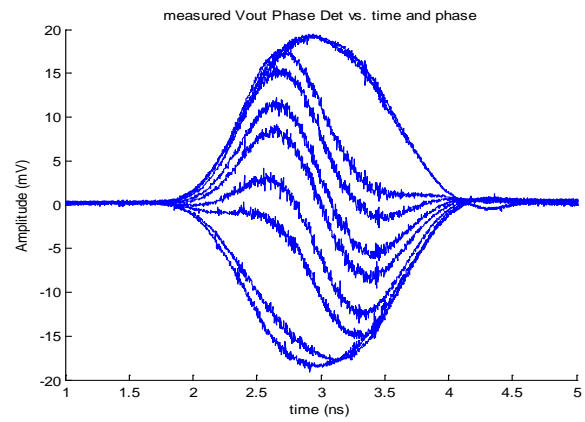Further work is required to verify our estimate of a 4X increase in sensitivity..

Figure 13: Time domain response of test phase detector

CONCLUSIONS AND FOLLOW ON IDEAS

One interesting aspect of this work with the 11.424 GHz comb generator is the recognition that at these frequencies, the generation of a clean beam-derived signal to drive the comb is a special concern. If one wants to use this technique at higher frequencies, the generation of the beam input signal requires special care to get the clean short tone burst signal at full amplitude. The best use of this comb circuit might be as a part of a pick-up electrode or vacuum structure itself, as this would allow the highest fidelity coupling to the bunched beam signal. This approach also is attractive in that it reduces the bandwidth requirements on associated feedthroughs and cable assemblies. Such an integrated processing electrode combining pickups and comb generators would be a very challenging and interesting microwave circuit design.

ACKNOWLEDGEMENTS

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