Otava's Tunable Filter Solutions for RF Sampling Architectures

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Introduction

Otava Inc. has recently released a family of compact and very linear band-pass tunable filters, addressing various filtering needs from 2.5 GHz up to 40 GHz. With their high-power handling capability (up to 1 Watts rms) as well as high linearity (IIP3 ~ +45dBm), these filters may be used almost anywhere in RF signal chains, enabling cost effective multi-band radio designs. This paper highlights the benefits of the OTFL101 tunable filter within a direct-RF transmitter chain built around a wideband RF-sampling DAC.

The OTFL101 Tunable Filter

The OTFL101 is a single chip tunable band-pass filter, which offers a tuning range between 2.5 and 7 GHz. It is not only compact, with a very small footprint of about 2.3x1.6 mm, but it also doesn't require any external components. It is controlled via a 3-wire serial interface taking 1.8 V CMOS signals (CLK, Data, Device Select). Multiple filters may be controlled via the same serial bus with dedicated device select signals.

The filter is a 5^{th} order design, for which each of the five capacitor banks or resonators may be configured individually, each with a 5-bit word.

The Figure 1 below shows overlayed S21 responses at five different center frequencies. Note that with simple tuning applied, the fractional bandwidth remains roughly constant over the tuning range.

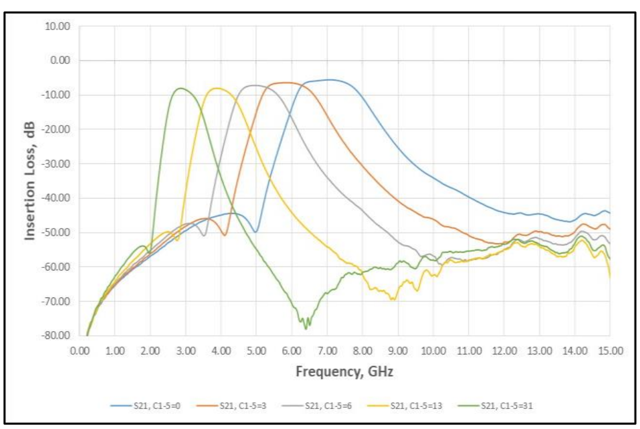

Fig. 1: OTFL101 S21 responses over the tuning range

RF-Sampling Architectures Filtering Requirements

In this paper, we are focusing on a particularly suitable application for this tunable filter: the output reconstruction filter for a high bandwidth direct-RF digital-to-analog converter (DAC).

While there are many RF-sampling DAC products on the market right now, the analysis performed here is based on the multi-channel AMD Xilinx Zynq® UltraScale+™ Gen3 RFSoC. This device enables high bandwidth RF-sampling, or direct-RF conversion, from DC to an output RF frequency of 6 GHz, with DACs sampling rate up to 9.85 Gsps. The on-chip digital up-converter, or DUC, is the digital modulator ahead of the digital-to-analog converter. Its high-resolution digital NCO enables high precision modulation to RF, removing the need for an external analog mixer or modulator.

Mixing terms through the complex modulator get replicated thru the DAC sampling process at the sampling rate of Fs, thus creating image tones at nFs +/-Fo, along with the wanted real signal at Fo. It is a common practice to apply a reconstruction filter directly post D/A conversion, to eliminate these unwanted terms before amplification.

The most dominant image tones at the DAC output are at the Fs-Fo and 2Fs-Fo frequencies. The following chart shows their frequency relative to the wanted signal at Fo, for a DAC sampling rate of 6.144 Gsps.

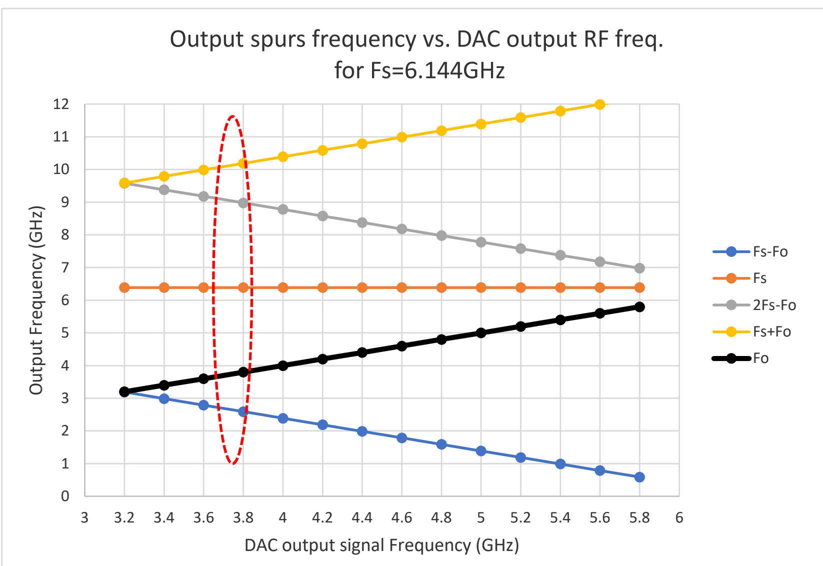

Fig. 2: Frequencies of the RF-sampling DAC output signals vs. Fo

From this chart, we can for instance extract the nearby tone frequencies for a desired output signal at Fo = 4 GHz:

- An image at 2.144 GHz [Fs-Fo image]
- Sampling clock leakage at 6.144 GHz [Fs leakage]
- An image at 8.288 GHz [2Fs-Fo image]
- An image at 10.144 GHz [Fs+Fo image]

Because of the DAC frequency roll-off past 6GHz, spurious and image tone beyond this cut-off frequency tend to be of lesser amplitude than Fs-Fo images which fall in-band, and therefore don't require as much filter selectivity.

In addition, for a given DAC sampling rate, the frequency separation between the wanted signal and its images changes as a function of the targeted RF output frequency. This means that the DAC reconstruction filter needs to be replaced or adjusted to track the wanted RF signal and provide adequate selectivity where needed.

The Benefits of a Tunable Filter

While RF amplifiers, VGAs and digital step attenuators have evolved to also support multi-GHz bandwidths out of a single device, the total signal chain cumulative pass-band selectivity is typically fixed and tailored to one particular band of operation. This requires a new bill of material for each band-specific design. With a tunable band-pass filter, Otava is now enabling multi-bands radios out of a unique small-signal RF chain, along with the ability to fine tune both the filter's center frequency as well as pass-band and specific out of band rejections. To aid with system-level optimizations, Otava is actually offering a Matlab-based behavioral model of the filter called the "OTFL101 Model Explorer App". This model may be downloaded using the link below.

https://www.mathworks.com/matlabcentral/fileexchange/106750-otfl101-model-explorer?s_tid=srchtitle

Being able to rely on a single tunable device is particularly important for an equipment maker when designing a radio for a multitude of cellular bands for instance, either for 4G LTE or 5GNR applications.

There is also a significant cost advantage, by re-using the same device across multiple platforms. Beyond the BOM cost advantages, there are also savings on both the R&D development time and testing efforts.

The following table provides a snapshot of how the OTFL101 tunable filter compares to existing off-the-shelf ceramic or LTCC filters.

Comparison chart with exiting fixed filters:

	Techno	Size (mm)	Pass-band (GHz)	IL (dB)	Rejection @-500MHz from the lower band edge	Rejection @+500MHz from the upper band edge
Filter 1	LTCC	3.2x1.6	2.8 – 4.6	1.5 - 3	-20	-10
Filter 2	LTCC	3.2x1.6	3.7 – 4.7	1.4 – 2	-10	-10
Filter 3	LTCC	3.2x1.6	2.57 – 3.44	2.2 – 3	-17	-25
Filter 4	Ceramic	1.6x0.8	3.3 – 3.8	1.8 – 3.2	-20	-15
OTFL101 tuned @4GHz	SOI	2.3x1.6	3.55 – 4.35	8 - 10	-35	-22

OTFL101 tuned @3GHz	SOI	2.3x1.6	2.7 – 3.3	8 - 10	-42	-24

As this summary table shows, the OTFL101 offers significantly higher selectivity compared to existing fixed frequency filters. While it has higher in-band insertion loss, the next section highlights how this can easily be mitigated without impacting cost, power consumption or performance.

Signal Chain Analysis and Comparisons with Fixed Frequency Filter

Here's a typical signal chain implementing a direct-RF transmitter (PA front-end not included here):

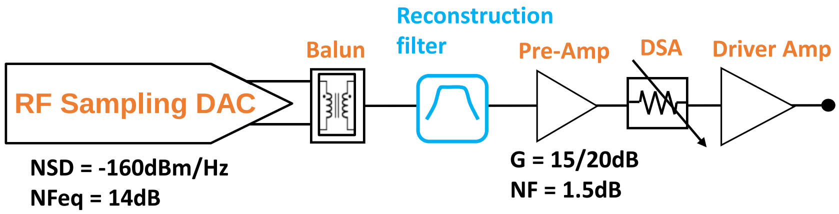

Fig. 3: Direct-RF transmitter block diagram

Let's now analyze the performance of this signal chain, comparing implementations with a traditional fixed filter against the one implementing the OTFL101 tunable filter, as the DAC reconstruction filter. The key metrics of interest here are going to be absolute output power level, SNR and output noise floor density.

Since the SNR performance of a transmit chain is dominated by the digital upconverter, modulator and small signal amplification chain, we can ignore the PA front-end here. For this analysis, we are also assuming operation at max gain setting (DSA at Min attenuation) and considering two variants of the same off-the-shelf wideband GaAs amplifier, post reconstruction filter, with either 15 or 20 dB of power gain (the QPA9126 and QPA9127 from Qorvo). Note that there is no impact in power dissipation between these two variants.

		Pout rms, PAR = 9dB	SNR (50MHz)	Output noise floor (dBm/Hz)
With fixed BPF	With 15dB Pre-amp (350mW)	6.5	69.4	-139.9
With OTFL101	With 15dB Pre-amp (350mW)	0.5	67.7	-144.2
	With 20dB Pre-amp (350mW)	5.5	67.9	-139.4

We can see that despite its higher insertion loss, the tunable filter only results in a 1.5dB SNR degradation over a fixed filter implementation, when using a higher gain amplifier post filter. This is mostly the result of 1dB lower output power level combined with a 0.5dB noise floor increase. The computed SNR is quite sufficient to drive a PA front-end, at near 68dB for a 50MHz modulated signal with 9dB PAR.

It is also worth noting that the tunable filter has no impact on output linearity performance and behaves as linearly as a fixed filter does.

Now that we've validated the signal chain from an SNR and linearity perspective, let's go over some test results and selectivity measurements pre and post filter.

Signal Chain Performance Results

The transmitter signal chain performance has been evaluated using the Xilinx development kit made of the AMD Xilinx ZCU208 card, and the XM655 balun board for the differential to single-ended conversion post DAC. The output of the balun is then directly connected to the OTFL101 evaluation board, which is then connected to an FSW spectrum analyzer from Rhode& Schwarz, as shown in the figure 4 below.

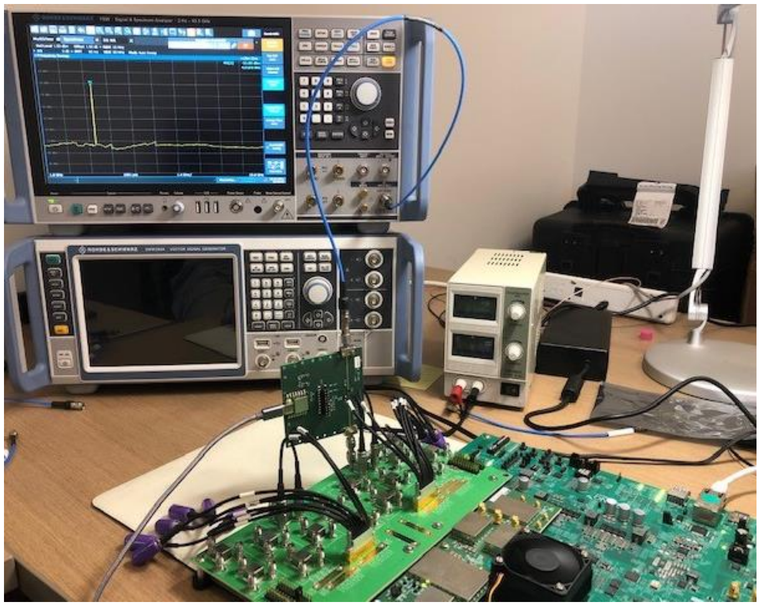

Fig. 4: Test Setup

Please note that all the results described here have not been de-embedded for the transmission lines and board interconnect losses.

In the particular test case shown below, the baseband CW signal is modulated to DAC RF output frequency of 4 GHz. The plot on figure 5 shows DAC output images along with the wanted signal at 4 GHz, over a 12 GHz span. The DAC sampling rate has been set to 6.144 GHz. We then observe, on figure 6, the output spectrum with filtering through the OTFL101 set to a center frequency of about 3.9 GHz.

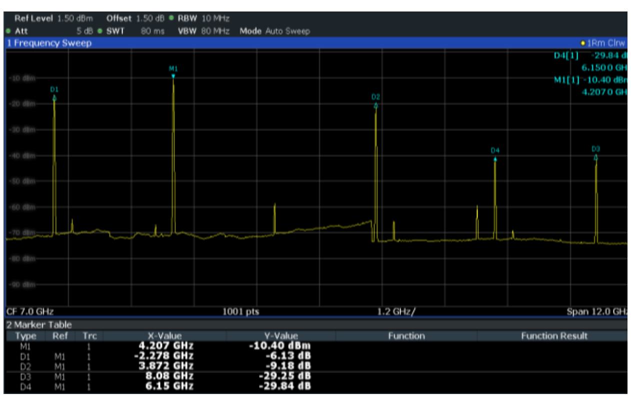

Fig 5: Before filtering post DAC, at Fo = 4GHz

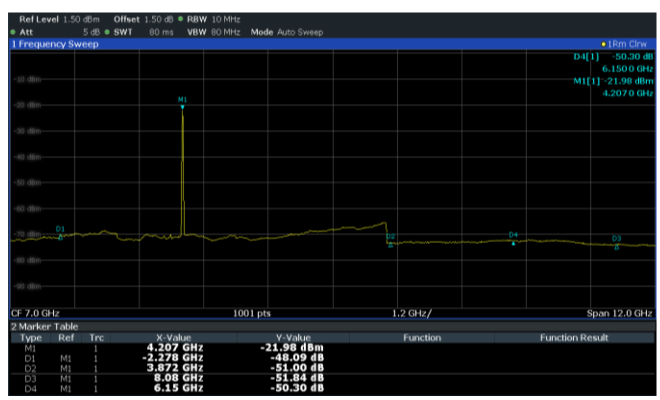

Fig 6: Post OTFL101 filtering

This shows more than 50dB rejection of the Fs-Fo image at -2.2GHz and 2Fs-Fo image at +3.88GHz from the wanted signal. Because of the wide span setting of the analyzer, the reduction in out-of-band noise floor is not visible here.

Next, let’s tune the filter to a different center frequency here, at around 5GHz, as shown on figure 7. We use the same exact procedure here, except for the DAC NCO frequency shift to place the wanted CW signal at 5 GHz, and the DAC sampling rate now set at 6.38976 GHz.

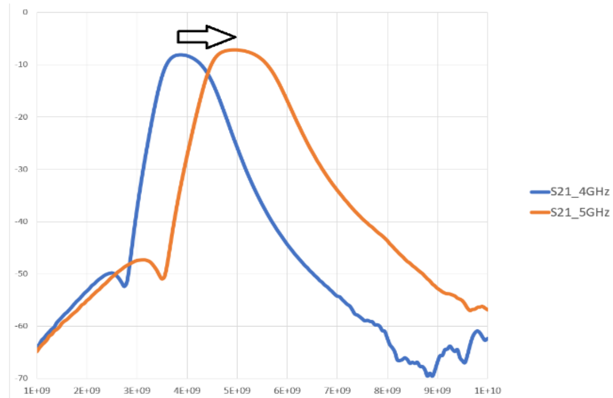

Fig 7: OTFL101 response from 4 to 5GHz Fc

The plot on figure 8 shows the DAC output images along with the wanted signal at 5GHz, over a 9GHz span. We then observe, on figure 9, the output spectrum with filtering through the OTFL101 set to a center frequency of about 5GHz.

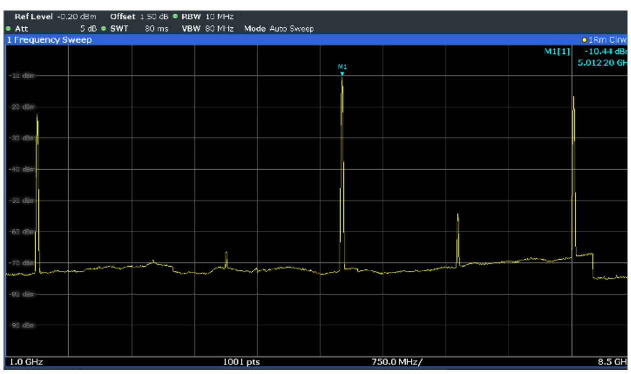

Fig 8: Before filtering post DAC, at Fo = 5GHz output

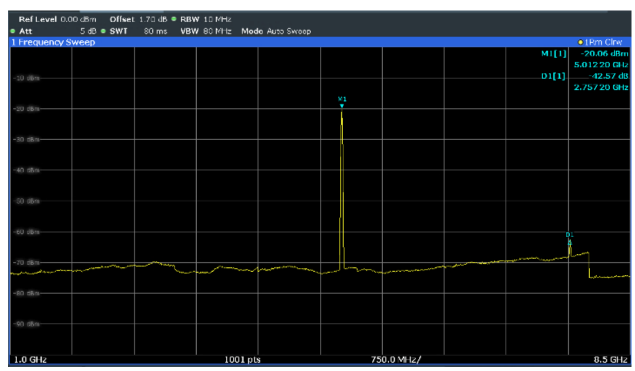

Fig 9: Post OTFL101 filtering

Again, the OTFL101 proves very effective in rejecting unwanted images, with more than 50dB rejection of the Fs-Fo image at 1.39GHz and 2Fs-Fo image at 7.78GHz. We basically get similar results over a wide range of RF output frequencies, making this RF lineup completely software programmable from 2.5 to 6 GHz.

Conclusion

Today’s RF-sampling architectures offer a lot of powerful capabilities, and along with very adequate RF performance, an attractive minimalistic bill of material for sub-6GHz MIMO applications. The small form factor tunable filter from Otava offers the ultimate complementary solution for a wideband software defined front-end signal chain. It is a very good fit for a tunable reconstruction filter post D/A conversion in RF-sampling architectures, offering more than 50 dB out-of-band rejection, sufficient to remove unwanted TX spurious and image terms ahead of the distributed RF amplification chain.