A 65 mW, 0.4-2.3 GHz Bandpass Filter for Satellite Receivers

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Abstract

A monolithic tunable bandpass filter for satellite receiver front-ends is demonstrated for the first time. The center frequency of the bandpass filter can be tuned from 0.4 GHz to 2.3 GHz. The filter is constructed using four gm-C filter sections and has a 50 dB variable gain range. At 20 dB attenuation and at 30 dB gain the measured 1 dB compression point is -21 dBm and -56 dBm, respectively. Measured IP3 is -12 dBm. The noise figure is 15 dB. An on-chip I/Q oscillator tracks the center frequency and enables automatic tuning. The bandpass filter dissipates 65 mW with 5 Volt supply voltage and occupies 0.16 mm^2 chip area.

Introduction

The zero-IF architecture is widely used to implement satellite receiver front-ends [1, 2, 3]. It allows a high degree of integration which reduces the cost price of satellite set-top boxes. A practical zero-IF front-end IC with its application is shown in fig. 1.

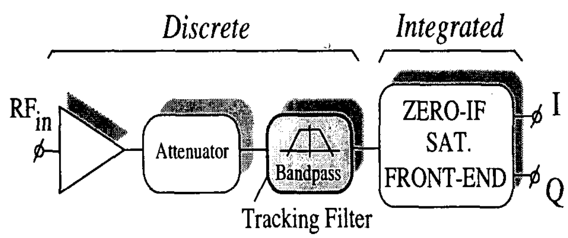

Figure 1. Satellite Front-end.

The typical application starts with an amplifier which implements a good VSWR and low system noise figure. Because total power of the 40 satellite channels can exceed 0 dBm, an attenuator is needed to relax IP3 and compression point requirements for the integrated Zero-IF front-end. The bandpass tracking filter reduces the total channel power further and reduces in particular the IP2 requirements. Long and lossy cables from satellite dish to set-top box cause tilt of the input spectrum which ranges from 950 to 2150 MHz. As a result, the carriers at 1 GHz may be more than 15 dB stronger than those at 2 GHz. For example, due to second order non-linearities, the channels around 1 GHz can cause spurious in the wanted channels at 2 GHz. By tuning the tracking filter to the wanted 2 GHz channel the 1 GHz interferers are reduced. In the Zero-IF IC the wanted channels are converted to I and Q baseband signals and channel selection takes place.

Fig. 1 illustrates that the degree of integration of a Zero-IF front-end can be further increased. A monolithic implementation of an attenuator for satellite front-ends is demonstrated by [1]. This paper presents the first monolithic prototype of the tracking bandpass filter. The realized bandpass filter can selectively amplify the wanted satellite channel from -20 dBm to +30 dBm. In addition an I/Q RC tracking oscillator is realized on the same die to enable automatic tuning.

Firstly, the system architecture of the IC will be presented in the next section. Secondly, the circuit implementation of one of the four cascaded gm-C filter sections will discussed. Thirdly, measurement results are discussed followed by conclusions.

System architecture

The block diagram of the IC is shown in fig. 2. The bandpass filter is constructed with four identical gm-C filter sections. Each section has a variable gain range of approximately 12.5 dB. The filter sections have In-phase (I) and Quadrature (Q) inputs and outputs. Since no I and Q signals are available at the RF-input, the I and Q inputs of the first stage are connected to RF_{in}.

The bandpass filter is controlled by three currents. The tuning current I_t controls the center frequency. I_t varies from 30μA to 390μA and gives a frequency range of 0.4 GHz to 2.3 GHz. I_b sets the bandwidth and ranges from 20μA till 90μA. I_b is used to keep the bandwidth approximately constant (250 MHz) over the complete tuning range. The third control current, I_g, controls the gain (12.5 dB range) and varies between 20 μA to 100μA.

In order to allow automatic tuning one filter section is copied and input and output are connected (see fig. 2). This implements a quadrature RC oscillator [4] which tracks the center frequency of the bandpass filter. The control currents of this oscillator are identical to the filter currents except for the gain setting current I_g. For accurate tracking, the

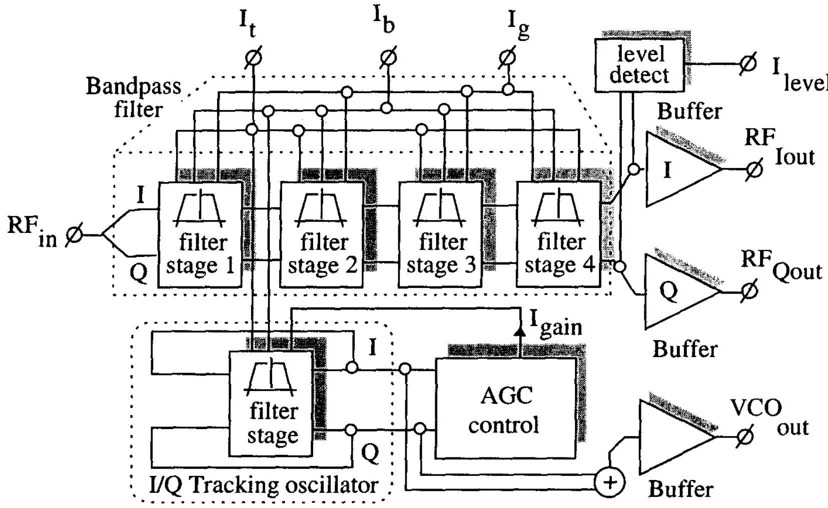

Figure 2. Block diagram of the bandpass filter with tracking oscillator.

oscillator amplitude must be controlled, since the effective transconductance of the oscillator will be reduced when the oscillator carrier signal becomes too large. In that case the carrier frequency drops and tracking is lost.

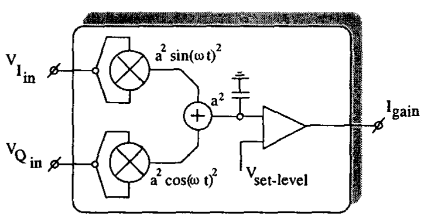

Figure 3. Blockdiagram of AGC control.

The Automatic Gain Control (AGC) is realized by making use of the oscillator I/Q-signals and is shown in fig. 3. AGC keeps the transconductances in the oscillator in the linear region.

The I and Q inputs of the first stage of the bandpass filter are driven by the RF input signal. As the I and Q parts of the filter section suppress the non-orthogonal frequency components, the quadrature relationship improves in each subsequent stage. Therefore, although the I and Q inputs of the first filter section are driven with a non-quadrature signal, the I and Q output of the fourth filter section are in quadrature (less than 6 degrees mismatch). Hence the level indication (I_{level} in fig. 2) is implemented in the same way as the AGC control of the oscillator (see fig. 3). Two open-collector buffers are cascaded after the four stage bandpass filter to enable RF measurements using 50 Ω load resistors.

Circuit implementation

The basic diagram of one filter section is shown in fig. 4. In this figure the three transconductances, g_t, g_b and g_d control the bandpass center frequency, bandwidth and gain.

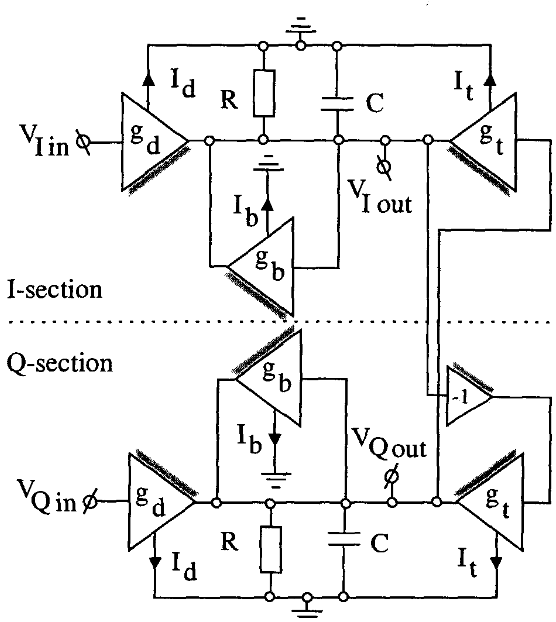

Figure 4. Behavioural model of one filter stage.

The center frequency is equal to $g_t/(2\,\pi\,C)$. Transconductance g_b in the I and Q sections implements a negative resistance of $-1/g_b$ which is in parallel with R. The resulting resistance R_{tot} is used to control the bandwidth of $1/(\pi\,R_{tot}\,C)$. The gain at the center frequency is $g_d\,R_{tot}$.

The circuit implementation of a filter stage is shown in fig. 5. All transconductances are implemented with 4:1 linearised differential pairs. In order to allow high frequency operation the capacitance C (fig. 4) is implemented using the device parasitics seen at the collector of the differential pairs of fig. 5. Each section is buffered with emitter followers, which is essential for operation above 1.5 GHz. The

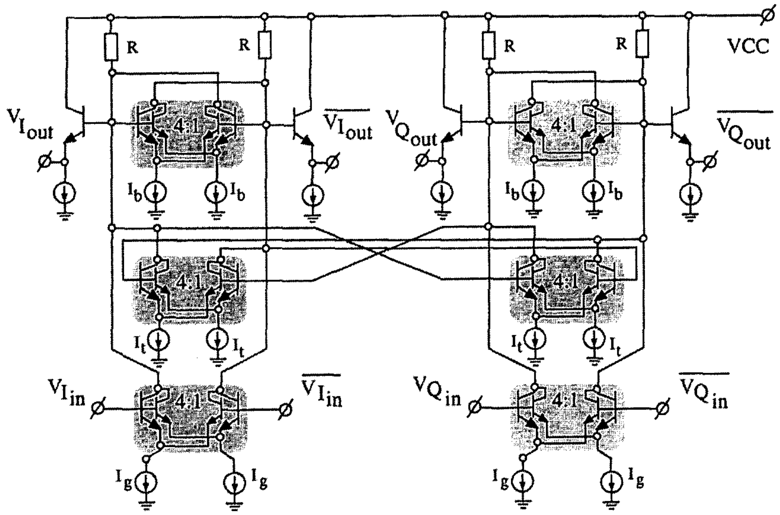

Figure 5. Simplified circuit diagram of one filter section.

buffers prevent the Miller-capacitances of the next stage from reducing the maximum stable frequency to below 1.5 GHz for high gain settings [5, 6]. The tracking oscillator circuit is identical to that of fig. 5 when the inputs of the I and Q section are connected to the outputs.

Measurement results

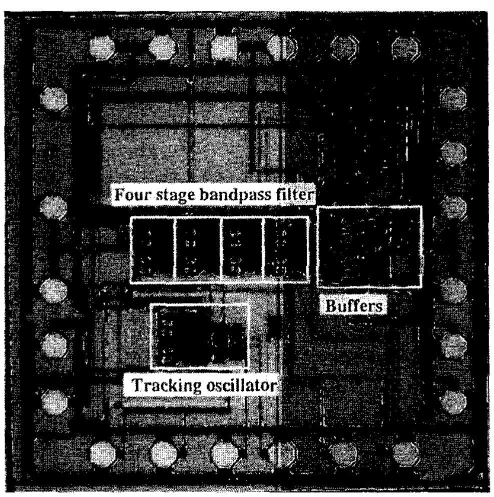

Figure 6. Micrograph of the IC.

The monolithic bandpass filter is realized in a standard bipolar 11 GHz f_t process. Measurements are performed on samples packaged in a 24-pins plastic SSO package. Fig. 6 shows a chip micrograph. Total chip area is 1.25 mm^2 of which the four filter sections occupy 0.16 mm^2. The total current consumption of the IC is 40 mA. The bandpass filter dissipates 65 mW and the tracking oscillator 14 mW with a 5 Volt supply voltage.

Fig. 7 and fig. 8 show the bandpass filter characteristics for 30 dB gain and 20 dB attenuation respectively. The gain control range is 50 dB and the tuning range of the filter is 0.4 GHz - 2.3 GHz. The main reason for the non-linear tuning curve is the influence of the base-emitter diffusion capacitance of transconductances g_t, which increases with increasing tuning currents I_t. The bandwidth is set to approximately 250 MHz, so that eight satellite channels of 30 MHz are passed. At 30 dB gain the noise figure is 15 dB and the input 1 dB compression point is -56 dBm. Measured input IP3 is -12 dBm. When the filter attenuates 20 dB the input 1 dB compression point is -21 dBm.

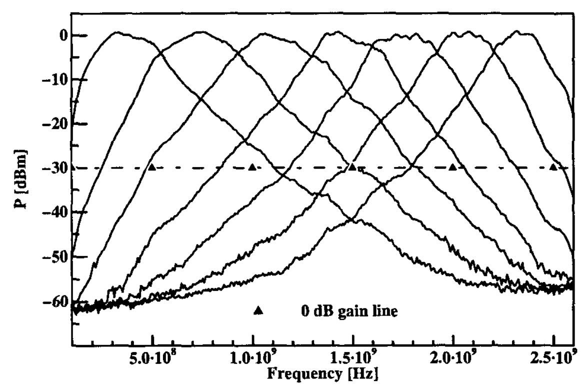

Figure 7. Measured bandpass curves for 30 dB gain setting.

Fig. 9 shows the center frequency of the filter and tracking VCO frequency. The feedback-connection of the driver-stages (g_d in fig. 4) in the oscillator resulted in a delay. This delay can be modelled as an additional capacitance in the oscillator. The delay is also present between the filter stages but only introduces a phase shift and does not influence the center frequency. Therefore, a frequency offset results with respect to the center frequency of the filter. For

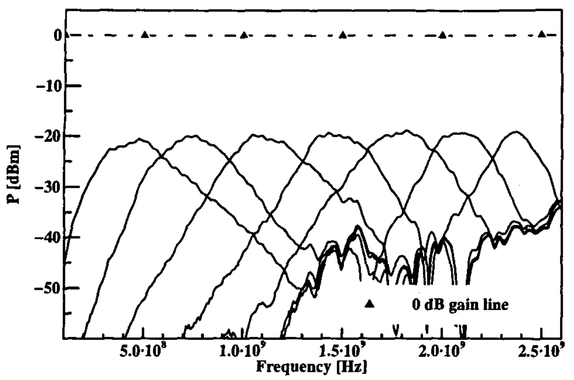

Figure 8. Measured bandpass curves for -20 dB gain setting. The high noise floor around 2 GHz is caused by the PCB and measurement equipment.

automatic tracking it is necessary that the frequency offset is approximately constant. Within the satellite band the ratio between the center frequency and VCO frequency is fixed at $1.165 \pm 2\%$ (see fig. 9(a)). Hence, tracking can be accurately implemented by a difference in divider ratio of the filter tracking Phase Locked Loop (PLL) and the PLL which is used for channel selection (LO frequency synthesiser).

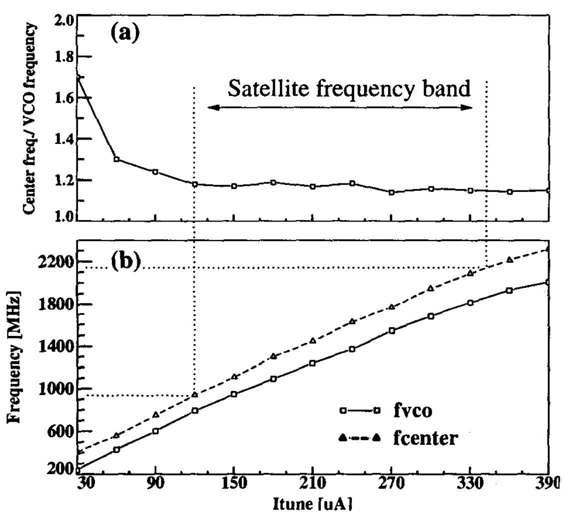

Figure 9. Measured ratio of the filter center frequency and VCO frequency versus I_{tune} (a). Frequency versus I_{tune} of the VCO and the bandpass filter (b).

Performance of the monolithic RF bandpass filter is summarized in table 1. The presented circuit demonstrates *for the first time* the feasibility of tunable integrated RF selectivity for satellite front-ends. When tuned to 2 GHz the realized bandpass filter attenuates interferers at 1 GHz by more than 45 dB (see fig. 7). Both noise figure and linearity can be further optimized. The noise figure can be reduced at the expense of increased power consumption and by optimising the gain distribution of the four stages.

Table 1. Bandpass filter performance summary.

Parameter	Value	Unit
Process	Bipolar	
f_t NPN	11	GHz
Active IC area	1.25	mm^2
Filter IC area	0.16	mm^2
Min. f_{center}	0.4	GHz
Max f_{center}	2.3	GHz
Min gain	-20	dB
Max gain	30	dB
Noise Figure	15	dB
1 dB compression	-21	dBm
IP3	-12	dBm
Vsupply	5	V
Total power	200	mW
Filter power	65	mW

Additional linearising techniques [7] can improve IP3 performance significantly. The implementation is realized using a high volume 11 GHz f_t bipolar process. Naturally, a more modern process (e.g. 30 GHz f_t) will have reduced parasitics and will yield additional performance improvement.

Conclusions

A prototype of an integrated bandpass filter for satellite receivers is demonstrated for the first time. A 50 dB gain control range is measured for frequencies ranging from 0.4 GHz to 2.3 GHz. Automatic tuning to the desired input channel is feasible with an on chip quadrature tracking oscillator.

Acknowledgement

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