A CMOS RF tunable filter for TV white space transmitter applications

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Abstract: A UHF-band RF tunable filter is developed for TV white space CMOS transmitter applications. It is based on the combined Sallen-Key and LC notch structure. The inherent transmission zero of the Sallen-Key core is carefully chosen to suppress the 7th-harmonic component of the transmitter output, and the LC notch filter is set to suppress the 9th-harmonic component. The filter is built in 0.18- μm CMOS process and consumes 6.2-mA from a 1.8-V supply. The filter's cutoff frequency is tuned from 100-MHz to 500-MHz in five steps. It is successfully adopted in a TV white space CMOS transmitter integrated circuit.

Keywords: RF tunable filter, Sallen-Key filter, harmonic rejection filter

Classification: Integrated circuits

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Fig. 1. Circuit schematic of RF tunable filter.

1 Introduction

The federal communications commission (FCC) has recently approved the unlicensed radio transmission in the TV white space band for digital data communication. With this, a new path to white space or Super Wi-Fi devices is cleared. The white space device can enable long-distance and robust wireless internet connection since the TV band is better for reaching farther with less attenuation compared to the existing 2.4 or 5 GHz airwaves. Along with IEEE 802.22 cognitive radio based wireless regional area network (WRAN) standardization, the TV-band CMOS transceiver implementation efforts have started to appear in the literature [2, 3].

In order not to interfere with the other TV band signals, the TV white space transmitter requires very low spurious emission level within the band. It can be achieved by embedding an RF tunable filter in the transmitter to reject the harmonic tones that are generated during frequency up-conversion procedure. A g_m -C filter can be a possible choice for this, but it is very vulnerable to nonlinearity under the transmitter's large voltage swing. A Q-enhanced active LC filter showed excellent selectivity performance, but suffered from narrow band coverage [4]. Another previous approach was to cascade two Sallen-Key stages in series [5]. Although the harmonics were successfully suppressed, its high current consumption due to the two cascaded stages was disadvantageous.

In this work, we present an efficient design approach for the RF tunable filter by combining the Sallen-Key core and an LC notch filter buffered by a source follower. By working with harmonic rejection mixer (HRM) in the transmitter, the RF tunable filter significantly rejects the in-band harmonic emission level in the TV white space transmitter [3].

2 Circuit design and results

The RF tunable filter is based on the combined Sallen-Key and LC notch structure. Since a conventional harmonic rejection mixer (HRM) [6] can suppress the 3rd, 5th, 11th, and 13th harmonics, this RF tracking filter is designed to reject the 7th and 9th harmonics. The inherent transmission zero of the Sallen-Key structure is beneficial for steep skirt characteristic at around 7th

Fig. 2. (a) AC equivalent circuit of the RF tunable filter. (b) Calculated transfer characteristics of the front part of the filter, that is the source follower and the LC notch filter.

harmonic frequency. In addition, the remaining 9th harmonic component is further suppressed by the LC notch filter. Compared to the previous cascaded Sallen-Key approach [5], it consumes less current and provides simple architecture.

Fig. 1 shows the circuit schematic. It consists of a source follower (M_{1,2}), an LC notch filter (L₁ and C₁), and a Sallen-Key core (M_{3,4}, R_{1,2}, C_{2,3}). By switching C₂ and R₂, the corner frequency is tuned from 100 to 500 MHz in five steps, and the transmission zero of the Sallen-Key stage is also controlled to be around 7th harmonic frequency. In accordance with the corner frequency tuning, the LC notch frequency is also tuned to the 9th harmonic frequency. In order to provide sufficient linearity with a large signal swing, the source follower is chosen as the filter's first stage due to its superior linearity. Even though the in-band gain of the source follower is slightly less than unity, it can be easily compensated by other blocks in the transmitter circuits via proper gain distribution.

The small signal equivalent circuit of the RF tunable filter is drawn in

Fig. 2 (a). The transfer function of the source follower with the LC notch is given by

$$\frac{v_x(s)}{v_i(s)} = \frac{s^2 + \frac{R_s}{L_1}s + \frac{1}{L_1C_1}}{\alpha s^2 + s\frac{1}{L_1}(\alpha R_s + g_{m1}^{-1}) + \frac{\alpha}{L_1C_1}} \quad (1)$$

where $\alpha = 1 + (g_{m1}r_{o1SF})^{-1}$ and, $r_{o1SF} = r_{o1} \parallel r_{oSF}$, R_s is the parasitic series resistance of L_1 , and r_{oSF} is the output resistance of source follower's current source. And the transfer function of the subsequent Sallen-Key filter is given by

$$\begin{aligned} & \frac{v_o(s)}{v_x(s)} \\ &= \frac{s^2C_2C_3R_2R_o + sC_2R_o + K}{s^2C_2C_3[R_1R_2 + (R_1 + R_2)R_o] + s[C_3(R_1 + R_2) + C_2(R_o + R_1(1 - K))] + 1} \end{aligned} \quad (2)$$

where $K = \frac{g_{m3}r_{o3SK}}{1 + g_{m3}r_{o3SK}}$, $R_o = \frac{r_{o3SK}}{1 + g_{m3}r_{o3SK}}$, $r_{o3SK} = r_{o3} \parallel r_{oSK}$, and r_{oSK} is the output resistance of Sallen-Key stage's current source. It should be pointed out that the transconductance g_{m1} of the source follower $M_{1,2}$ must be carefully chosen to achieve optimum rejection characteristic by the LC notch. Eq. (1) indicates that the attenuation at the notch frequency $\omega_0 = 1/\sqrt{L_1C_1}$ is $R_s/(\alpha R_s + 1/g_{m1})$ and the filter's Q factor is approximately given by $g_{m1}\omega_0L_1$. Hence, lowering g_{m1} will increase the attenuation while degrading the filter's Q and vice versa as illustrated in Fig. 2 (b). In this design, g_{m1} is optimally set to 16.8 mS with $L_1 = 2.6$ nH and $R_s = 4.9 \Omega$, resulting in the peak attenuation of about -17 dB.

The RF tunable filter is fabricated in a 0.18- μ m CMOS process and integrated with a TV-band CMOS transmitter. Fig. 3 (a) shows the chip micrograph. The active area is $685 \times 450 \mu\text{m}^2$. The top metal layer is used for the signal path for minimum parasitic capacitance with respect to the ground plane. And the signal line is drawn as short as possible in order to reduce path loss. The chip is packaged in a 48-pin leadless plastic chip carrier (LPCC) and tested on an evaluation board. The filter consumes 6.2 mA from a 1.8-V supply. Fig. 3 (b) shows the measured transfer characteristics. This measurement was performed with an added external amplifier to drive 50- Ω load and its 12-dB gain is de-embedded. The filter shows 2-dB in-band loss. The cutoff frequency is tuned from 100 to 500 MHz in five steps. The effect of LC notch filter on far-out stop-band attenuation is demonstrated in Fig. 3 (c) for the cases of 100- and 200-MHz cutoff frequencies. It can be observed that the far-out stop-band attenuation is significantly improved when the LC notch filter is activated. The maximum improvement of stop-band attenuation is almost 17 dB when the cutoff frequency is 100 MHz. As a result, in the final full transmitter circuit measurement [3], the 7th harmonic component is found to be dramatically suppressed by 24.6 dB when the RF tunable filter is activated. Further measurements show that the in-band harmonics are always below -42 dBc across the full TV-band thanks to the significant

Fig. 3. (a) Chip micrograph. (a) Measured filter transfer characteristics with cutoff frequency tuning. (b) Measured effects of the LC notch. (d) Performance summary of the filter.

contribution of the RF tunable filter. The measured performances of the RF tunable filter are summarized in Fig. 3 (d).

3 Conclusion

An RF tunable filter has been developed for TV white space transmitter applications. By combining the Sallen-Key structure and the LC notch filter, the 7th and 9th harmonic components are effectively suppressed with low current consumption. A small signal transfer function analysis is presented for finding the optimal design condition of the source follower followed by the LC notch. The measurement results prove that the proposed RF tunable filter can be successfully employed for the TV white space transmitter applications.

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