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An 880 / 1760 MHz Dual Bandwidth Active *RC* Filter for 60 GHz Applications

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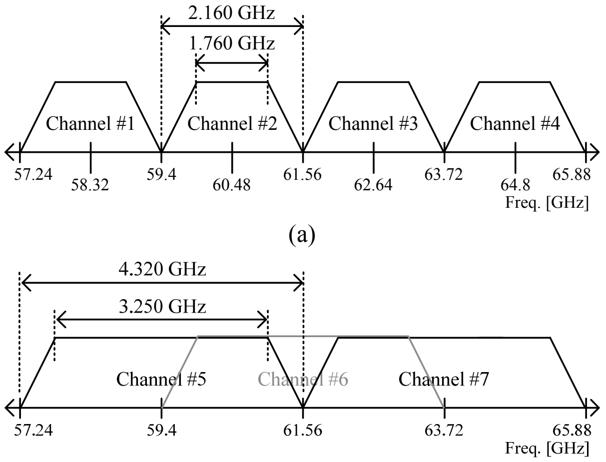
Abstract**—**An active *RC* filters with a 880 / 1760 MHz dual bandwidth tuning ability is present for 60 GHz unlicensed band applications. A third order Butterworth low-pass filter utilizes two Cherry-Hooper amplifiers to satisfy the very high bandwidth requirements of an amplifier. The low-pass filter is fabricated in 90nm standard CMOS process. Drawing 6.7 mW from 1.2 V power supply, the low frequency gains of the filter are -2.5 and -4.1 dB, and the output third order intercept points (OIP_3) are +2.2 and +1.9 dBm for the single channel and channel bonding conditions, respectively.

Keywords**—**Butterworth filter, active *RC*, 60 GHz, CMOS, dual bandwidth, Cherry-Hooper amplifier.

I. INTRODUCTION

MILLIMETER-WAVE wireless communication, based on 60 GHz unlicensed band, becomes a key technology in order to satisfy soaring demands on a Gbps ultra high speed data rate for transferring high quality multimedia contents in wireless environment without any time delay. This unlicensed band is available in many countries. The frequencies from 57 to 64 GHz are reserved in North America and South Korea, from 59 to 66 GHz in Europe and Japan [1], [2], and will be adopted by many rising countries over the world. There are several wireless communication standards, such as the IEEE 802.11ad [3], IEEE 802.15.3c [4], Ecma387 [5], Wireless HD [6], and WiGig [7], to utilize the 60 GHz band. Fig. 1 shows the channelization with and without channel bonding in the 60 GHz unlicensed band from 57-66 GHz [3]-[5].

The key to proliferate 60 GHz applications is to build a low cost chipset. A single chip solution using the complementary metal oxide semiconductor (CMOS) process becomes more promising, as the transit frequency of a CMOS transistor is now as high as several hundred GHz [8]. However, CMOS implementations for 60 GHz applications show lots of problems to solve. The front-end RF parts suffer from the high operating frequency, the analog baseband parts is in troubles due to the wide bandwidth requirement. The baseband filter performs channel selection as well as out-of-band interference rejection in the receiver path to relax the dynamic range requirements for the following stages such as a variable gain amplifier and analog-to-digital converter, and defines the spectrum of a signal by suppressing out-of-band spectral leakages in the transmitter path to satisfy the spectral mask requirements. As shown in Fig. 1, the required baseband filter bandwidths are 880 and 1760 MHz for the single channel and channel bonding conditions, respectively. Thus, there is no simple method to satisfy this wide bandwidth. An 880 / 1760 MHz dual bandwidth active *RC* filter is implemented in 90 nm standard CMOS process.



(a)

(b)

Fig. 1 Channelization in the 60 GHz band (a) without channel bonding, (b) with channel bonding

This paper is organized as follows: A third order Butterworth low-pass filters is presented in Section II, where a Cherry-Hooper amplifier is present to utilize its inherent very wide bandwidth. Section III reports the experimental results of the filter. Conclusions are presented in Section IV.

II. ACTIVE *RC* LOW-PASS FILTER DESIGN

A. Wide Bandwidth Filter for CMOS Integration

Microelectromechanical systems or Surface acoustic wave filters show excellent filter performance at GHz applications [9]-[12], but they have inevitable size and cost issues. The tunable impedance technique for RF filters is recently proposed, but it is only effective for band-pass or band-stop applications [13]. The passive filter implementation can

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guarantee both the wide bandwidth and accurate tuning performance, but the necessity of inductors limits its applications [14]. The popular integrated approach is an active filter such as active *RC* and *Gm-C* filters. However, the active filter suffers from the finite low frequency gain and bandwidth of an operational amplifier or operational transconductance amplifier. Both active *RC* and *Gm-C* filters are good candidates for wideband applications without external elements. However, a *Gm-C* filter suffers from the poor linearity as well as large process and temperature variations, even if it is efficient in low power applications [15]. Thus, the active *RC* filter is focused in this paper.

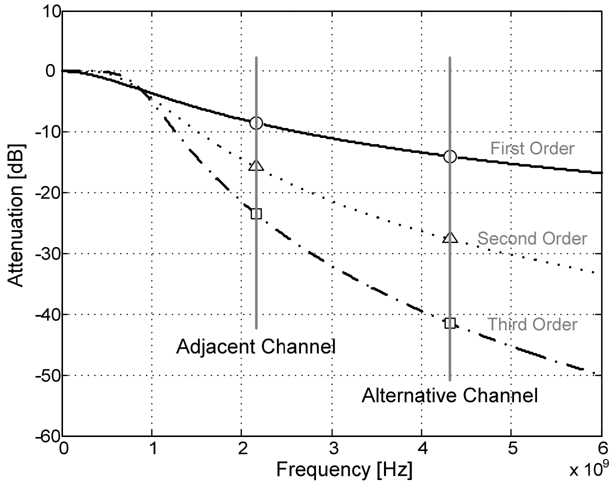


Fig. 2 Out-of-band interference suppression for second, third, and fourth order Butterworth filters

Due to severe atmosphere condition around 60 GHz frequency band, the wave propagation is highly attenuated by 5-30 dB/km, and wave penetration experiences serious loss in common materials [16], [17]. Therefore, the beamforming is one of the most important techniques in 60 GHz applications to increase the wireless connection range, and the beamforming technique is intrinsically effective to decrease the interference problem between nearby devices. Moreover, the standards, based on the 60 GHz unlicensed band, does not clearly define the interference level. Fig. 2 illustrates the attenuation level for different orders of Butterworth filters. For a third-order Butterworth filter, the interference powers at the adjacent channel and an alternative channel are suppressed by -23.4 dB and -41.5 dB at the center frequencies of each channel, as shown in Fig. 2. This suppression level is good enough for the low interference conditions in the 60 GHz band. Fig. 3 shows the structure of a third-order Butterworth filter, based on the Tow-Thomas biquad [18]. The transfer function of the third-order Butterworth filter is given by:

$$\frac{V_{out}}{V_{in}}(s) = -\frac{\left(R/R_G \right)}{R^3C^3s^3 + 2R^2C^2s^2 + 2RCs + 1}, \quad (1)$$

where the required filter coefficients can be set by *R* and *C*, and the filter gain is controlled by R_G. For a unity gain third order Butterworth low-pass filter, the Capacitors of 100 fF are chosen, and the tunable resistors of 900 / 1800 Ω are used for the single channel and channel bonding selection.

B. Amplifier Design

The third-order Butterworth filter includes two amplifiers, as shown in Fig. 3. Since the performances of the third-order Butterworth filter are degraded by the non-ideal characteristics of an amplifier, the amplifier bandwidth should be high enough to sustain sufficient gains beyond the desired filter bandwidth. As a rule of thumb, the required gain-bandwidth product of an amplifier should be at least ten times larger than the desired filter bandwidth [19].

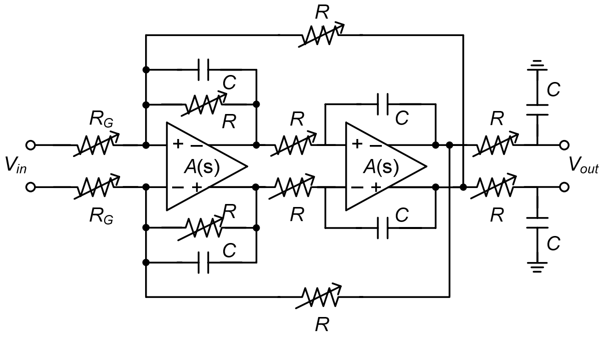


Fig. 3 A third order Butterworth low-pass filter based on the Tow-Thomas biquad, where *A*(s) denotes the transfer function of an amplifier

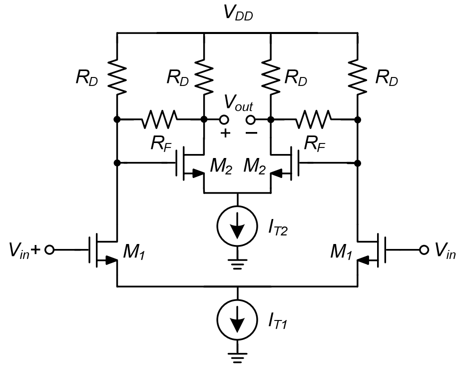


Fig. 4 A modified Cherry-Hooper amplifier

A Cherry-Hooper amplifier has very efficient structure to increase its bandwidth [20]. A modified Cherry-Hooper amplifier is shown in Fig. 4, and its gain and phase responses of the designed Cherry-Hooper amplifier are shown in Fig. 5 [21]. In order to include loading effects, the feedback components of the third order Butterworth filter in Fig. 3 are considered in Fig. 5. However, there is a trade-off between gain and bandwidth in the Cherry-Hooper amplifier. The signal in the Cherry-Hooper amplifier is transferred only through the low impedance nodes, and so its structure is optimized to maximize the amplifier bandwidth. On the other hand, the low frequency gain of the Cherry-Hooper amplifier is quite limited.

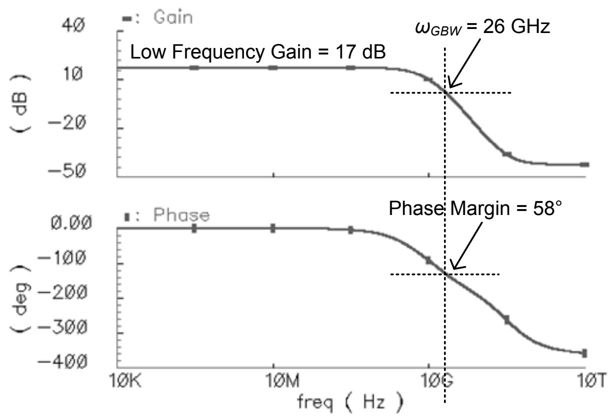


Fig. 5 The gain and phase responses of the Cherry-Hooper amplifier

III. EXPERIMENTAL RESULTS

The 880 / 1760 MHz dual bandwidth third order Butterworth low-pass filter are implemented in 90 nm standard CMOS process. Fig. 6 shows the filter chip photograph, where the occupied chip area is 240 × 230 μm^2. Note that the third order Butterworth low-pass filter is connected to the pad through an output buffer, as shown in Fig. 6. The output buffer with 0 dB gain, 50 Ω terminations and 17.2 mW power consumption is intentionally designed for the purpose of stand-alone filter measurement. From 1.2 V power supply; the third order Butterworth low-pass filter consumes 6.7 mW, independent of the bandwidth selection.

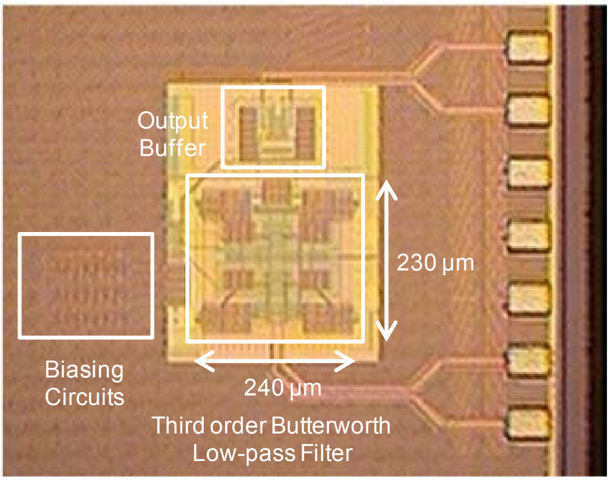


Fig. 6 Designed filter chip photograph

The measured -3 dB bandwidths for the single channel and channel bonding conditions are 890 and 1760 MHz, respectively, as shown in Fig. 7. The low frequency gains for the single channel and channel bonding conditions are -2.5 and -4.1 dB, respectively. Note that variations due to the measurement peripherals, including cables, PCB, and baluns, are deembedded by subsequent measurements. Since the bandwidth selection is controlled by the tunable resistors, the loading effects of the filter components changes the low frequency gain of Cherry-Hooper amplifiers, and so the low frequency gain of the overall filter performances decreases as the -3 dB bandwidth of the filter increases.

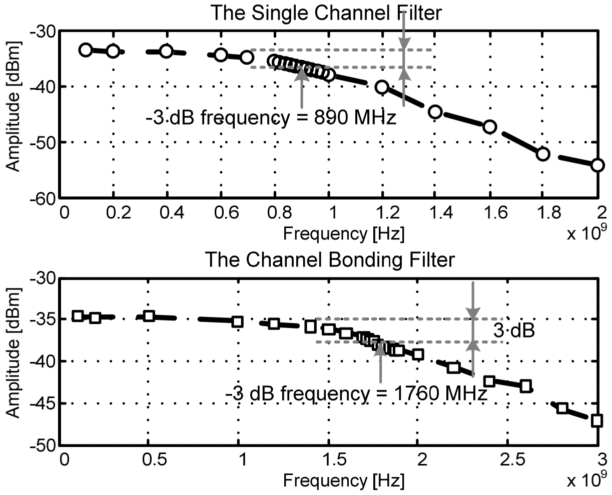
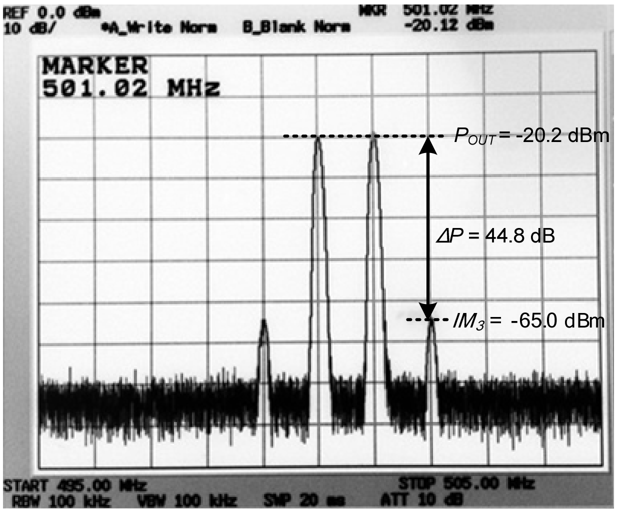


Fig. 7 Measured -3 dB bandwidths for the single channel and channel bonding filters

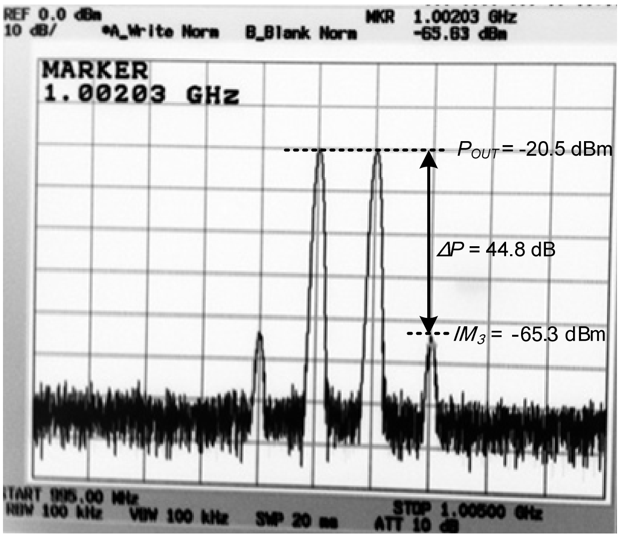
TABLE I
880 / 1760 MHz DUAL BANDWIDTH THIRD ORDER BUTTERWORTH LOW-PASS FILTER PERFORMANCE SUMMARY

Performances	880 MHz Bandwidth Case	1760 MHz Bandwidth Case
Technology	CMOS 90 nm	
Power Supply	1.2 V	
Die Area	0.055 mm^2 (240 × 230 μm^2)	
Filter Function	Third Order Butterworth LPF	
-3 dB Bandwidth	890 MHz	1760 MHz
Low Frequency Gain	-2.5 dB	-4.1 dB
In-band OIP_3	+2.2 dBm[1]	+1.9 dBm[2]
Power Consumption	6.7 mW[3]	

1. Measured with two tone inputs at 500, 501 MHz. 2. Measured with two tone inputs at 1000, 1001 MHz. 3. Power consumption for the filter core block only.



(a)



(b)

Fig. 8 In-band IM_3 (a) for the single channel filter with two tones at 500 and 501 MHz, (b) for channel bonding filter with two tones at 1000 and 1001 MHz

The third order intermodulation products, so called IM_3 products, are measured to estimate the filter linearity. Fig. 8 shows the in-band IM_3 products. The OIP_3 can be estimated by

$$OIP_3 = P_{OUT} + \frac{1}{2}\left|\Delta P\right|, \tag{2}$$

where P_{OUT} and ΔP denote the output signal power in dBm and the power ratio between P_{OUT} and IM_3 products in dB [22]. Then, the corresponding OIP_3 is +2.2 and +1.9 dBm , and the input third order intercept point (IIP_3) is given by +4.7 and +6.0 dBm with the filter gain for the single channel and channel bonding conditions, respectively. The single channel case shows better linearity performance than that of the channel bonding case because the feedback components of the filter changes the performance of Cherry-Hooper amplifiers. Table I summarizes the performances of the 880 / 1760 MHz dual bandwidth third order Butterworth low-pass filter.

IV. CONCLUSION

A third order Butterworth low-pass filter with an 880 / 1760 MHz dual bandwidth tuning ability is designed. In order to satisfy the wide bandwidth requirements of the Butterworth low-pass filter, the modified Cherry-Hooper amplifier is utilized for its wide bandwidth ability. The third order Butterworth low-pass filter using Cherry-Hooper amplifiers is implemented in 90 nm standard CMOS process, and consumes 6.7 mW from 1.2 V power supply. The measured $OIP3$ are +2.2 and +1.9 dBm, and the low frequency gains are -2.5 and -4.1 dB for the single channel and channel bonding conditions, respectively.

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