On-Chip Monolithic Filters for Receiver Interference Suppression using Bond-Wire Inductors (Student Paper)

H. Khatri, L.E. Larson, D.Y.C. Lie

Center for Wireless Communication, University of California, San Diego
La Jolla, CA 92093, USA

ABSTRACT — **Two passive LC filters are fabricated in a 0.18 μm BiCMOS process for interference suppression in WCDMA applications. A single-pole filter achieves an insertion loss of 1dB at 2.14GHz and suppression of 12dB at 1.95GHz, while the three-pole filter has insertion loss of 8dB at 2.3GHz and provides a suppression of 23dB at 2.1GHz. Both filters are implemented using MIM capacitors and bond wire inductors.**

Index Terms — **Passive LC Filter, WCDMA.**

I. INTRODUCTION

In a frequency division duplex (FDD) system, the transmitter (TX) signal can leak into the receiver path through the duplexer, desensitizing the receiver and leading to intermodulation and cross-modulation interference [1] (Fig. 1). This imposes a high linearity requirement on the LNA and the mixer, and is typically solved by improving LNA linearity and by suppressing the transmitted signal by insertion of an external SAW filter between the LNA and the mixer. A variety of techniques have been developed to improve the linearity of the LNA and the mixer without substantially increasing the power consumption. However, to relax the stringent linearity requirements of the mixer, in practice an external SAW filter is still required which significantly increases the transceiver cost and size. This paper aims at finding on-chip solutions to eliminate the SAW filter in applications that require modest TX leakage attenuation.

The filter is required to have a low Noise Figure (NF) and exceptional linearity. Active RF filters often employ Q-enhancement techniques, and fail to meet the NF and linearity requirements in addition to consuming considerable dc power [2]. This leaves the passive LC filter as the only on-chip filtering option, although on-chip spiral inductors historically suffers from their low Q's, which creates high loss in the passband of the filter.

Filters designed for operation at 2GHz have inductance values in the sub-nH range, which provides the unique opportunity to replace the on-chip inductors with bond wires, eliminating the need for bulky low Q on-chip inductors [3]. The bond wires are found to have a self-inductance of ~1nH/mm and Quality factors in excess of 50 [4]. There are many drawbacks to bond wire-based filter designs. In particular, the range of realizable inductance values is quite limited, and the optimum configuration has one terminal of the inductor grounded. In order to improve their manufacturability, the filters we propose employ equal-valued grounded inductors (grounded to the package). The key design challenge then becomes the transformation of an LC prototype filter into the appropriate grounded inductor structure.
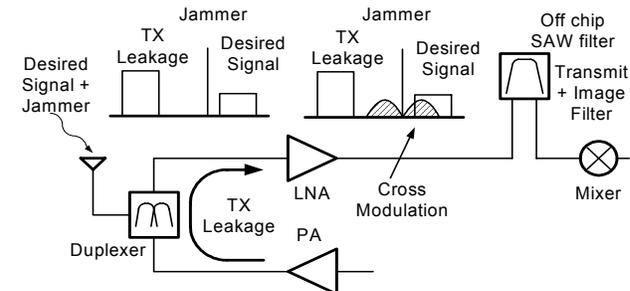

Fig. 1.   Cross-modulation in FDD CDMA Systems [1]

II. FILTER REQUIREMENTS

A. WCDMA Specifications

The requirements on the transmit leakage filter can be quite severe, which is why SAW filters remain the technology of choice for most applications. As one example of the challenging requirements, the RF receiver specifications of a WCDMA transceiver can be obtained from the 3GPP standard test conditions [5]. For a typical direct conversion receiver architecture, the specifications for the LNA and following band-pass filter are enumerated in Table I [6].

The IIP3 of the BPF should be such that its contribution to the effective IIP3 at the LNA input should be negligible (<10%) as compared to the LNA contribution. Thus,

$$\text{IIP}_{3,\text{BPF}} \geq 10\text{dB} + G_{\text{LNA}} + \text{IIP}_{3,\text{LNA}} = 22\text{dBm} \quad (1)$$

where, G_{LNA} is the LNA gain in dB.

TABLE I
LNA AND BPF SPECIFICATIONS FOR WCDMA

SPEC.	LNA	BPF
Gain in Rx Band(dB)	15±1	-2±1
Rx/Tx selectivity(dB)	>0	>21
Noise Figure(dB)	<2.5	<3
IIP_3(dBm)	>-3	>22

This relationship also implies that the insertion loss of the BPF can be traded with LNA gain provided the BPF has high linearity. For instance, if BPF insertion loss is 5dB, then LNA should be designed for 18dB and the BPF IIP_3 should be 25dBm.

B. Q-factor Requirements

For WCDMA, the transmitter and the receiver frequency bands are 1920-1980MHz and 2110-2170MHz respectively. This requires a fractional bandwidth of 2.8% which can be achieved only through
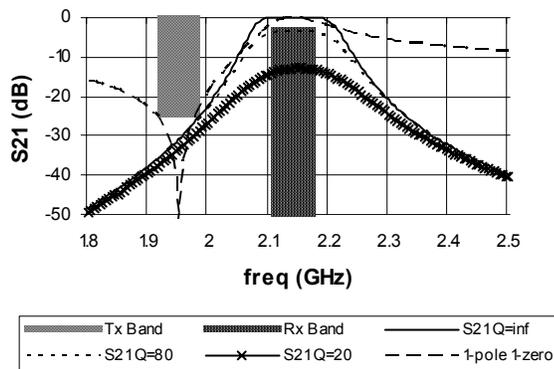
Fig. 2. Ideal S_{21} response for 3-pole and single-pole single-zero filter.

high Q components. Fig. 2. shows the WCDMA passband and stopband specifications. An ideal third order Chebyshev LC filter can meet this requirement (solid line); however, as the inductor Q drops to 20, the passband insertion loss increases drastically to ~12dB. Unlike insertion loss, the stopband suppression increases moderately, affecting the filter selectivity. The insertion loss problem can be partly addressed by using high Q components and by increasing the filter bandwidth. Introducing a zero in the stopband can improve the selectivity.

C. Bond Wire Considerations

The electrical characteristics of a bond wire are dependent on the physical geometry of the bond wire. They also depend on the crosstalk with neighboring bond wires. Ansoft HFSS 3D simulations are performed on single,

double and triple bond wires to study the variation of self inductance and mutual inductances of the bond wires with the physical parameters – height and horizontal length of the bond wire.
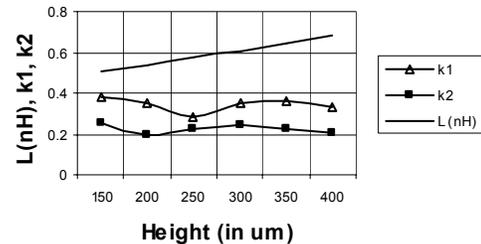
Fig. 3. Variation of coefficient of mutual inductances k_1, k_2 and self inductance L of bond wire with height.
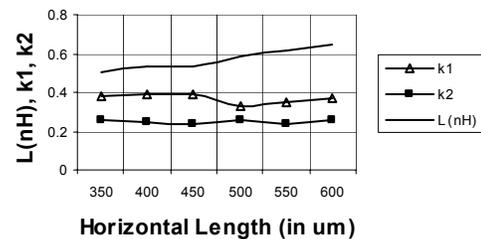
Fig. 4. Variation of coefficient of mutual inductances k_1, k_2 and self inductance L of bond wire with the horizontal length.

It has been found that self inductance increases steadily with the bond wire length. However, the coefficients of mutual coupling with the adjacent bond wire (k_1) and with the next to adjacent bond wire (k_2) are contained within a small range as height and horizontal length are varied (Figs. 3,4.). The mutual coupling decreases as the bond pad pitch is increased. Thus, for a given bond pad pitch, the coefficients of mutual inductances can be accurately estimated. Automated bonding process can deliver reproducible equal length parallel bond wires (0° angle between bond wires), which would result in a filter frequency translation if different from the desired length.

D. Pole Splitting due to Mutual Inductance

Unfortunately, the mutual inductance between the bond wires results in pole splitting. Consider the filter in Fig. 7(b). The pole locations can be obtained through the even and odd mode half circuits (Fig. 5). For the even mode, the poles are given by the roots of Eq. (2), whereas the odd mode resonates at a frequency given by Eq. (3). If k is the coefficient of mutual inductance between L_1, L_2 and L_2, L_3, then the resultant even mode half circuit has L_1 and $2L_2$ linked with coupling coefficient of 2k, while the odd mode half circuit remains unaltered with ω_{odd} still given by Eq.

(3). The new poles locations of even mode are the roots of Eq. (4). It can be shown that as k increases the roots of Eq. (4) move away.
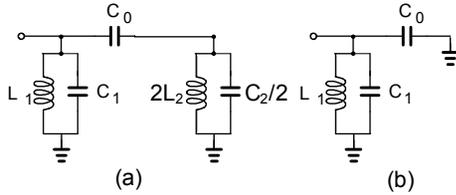

Fig 5. (a) Even mode half circuit. (b) Odd mode half circuit.

$$(1+s^2 L_1 C_1)(1+s^2 L_2(C_2+2C_0)) + s^2 L_1 C_0(1+s^2 L_2 C_2) = 0 \tag{2}$$

$$\omega_{odd} = \frac{1}{\sqrt{L_1(C_1+C_0)}} \tag{3}$$

$$(1-k^2)L_1 L_2(2C_0 C_1 + C_0 C_2 + C_1 C_2)s^4 + (L_1(C_1+C_0)+L_2(C_2+2C_0)-2kC_0\sqrt{2L_1 L_2})s^2 +1 = 0 \tag{4}$$

III. CIRCUIT DESIGN

It is shown that a third order Chebyshev filter can achieve the required specification. Another practical approach is a single pole single zero (SPSZ) notch filter. The two designs are discussed in detail.
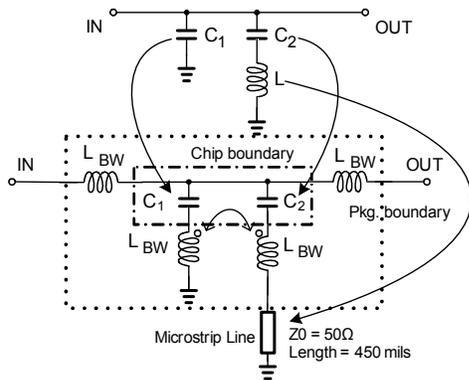

Fig. 6. SPSZ filter schematic. The transformation from lumped prototype to bond-wire implementation is shown. The passband occurs at the parallel resonance, and the stopband occurs at the series resonance of C_2 and L.

A. Single Pole Single Zero Interference Suppression Filter

The SPSZ filter is designed for modest suppression of the TX leakage power and low pass-band loss. As shown in Fig. 6, the series combination of C_2 and the inductance L creates a notch in the stop band (at 1.95GHz TX frequency).

At 2.14GHz the C_2-L branch acts inductively, which shunt resonates with C_1 to create a pole in the receive band. For on-chip implementation, C_1 is connected to the ground plane through a down bond creating a parasitic zero at higher frequency which deteriorates the insertion loss. This problem can be alleviated by reducing C_1 and by increasing L. The resulting large inductance in series with C_2 is implemented through a metal trace on the printed-circuit board along with the bond wire inductance.

B. Three Pole Interference Suppression Filter

The three pole filter is designed for larger suppression of the TX leakage, at the expense of higher insertion loss in the pass band. The band pass filter is derived from the third order Chebyshev low pass prototype (Fig. 7).
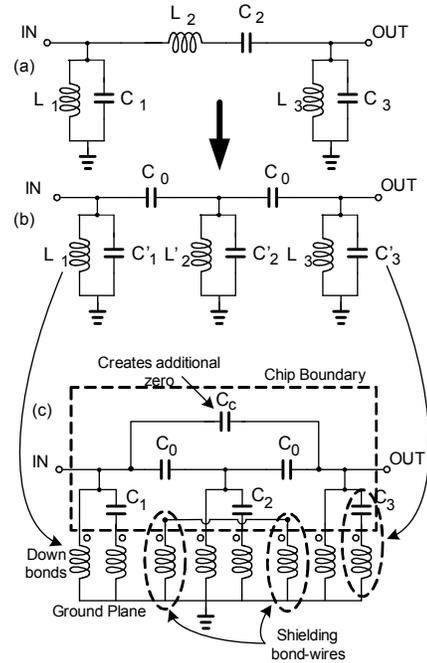

Fig. 7. Three-pole filter schematic. The transformation from lumped prototype (a) to top-C coupled prototype (b) to bond-wire implementation (c) is shown, and the final configuration uses grounded bond wire inductors only.

It is then transformed into top-C coupled resonator topology, which renders all the inductors equal sized and reduces disparity among the capacitor sizes. The inductors are realized with bond wires to ground and the capacitors are resized to take into account the effect of down bond inductance on their reactance (Fig. 7).

The mutual inductance between the bond wires must be accounted for while designing the filter. Within a shunt resonator section, the mutual inductance reduces the effective self inductance of the bond wires and thus translates the pass band to higher frequencies. Redesigning the filter for lower frequency can solve this. However,

mutual inductance between the bond wires of adjacent resonators has adverse pole-splitting affect. This can be avoided by introducing additional shielding down bonds between the resonators. The bypass capacitor C_c further improves the suppression in the stop band.

IV. MEASURED RESULTS

The microphotographs of the single-pole single-zero filter and the three pole filter are shown in Fig. 8. The SPSZ filter has a measured insertion loss of 1dB at 2.14GHz and TX suppression of 11dB at 1.95GHz (Fig. 8)
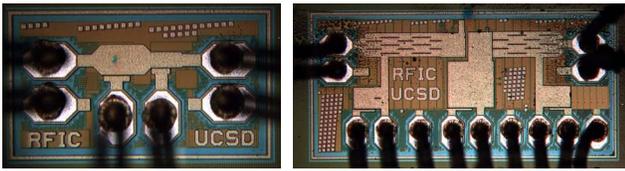

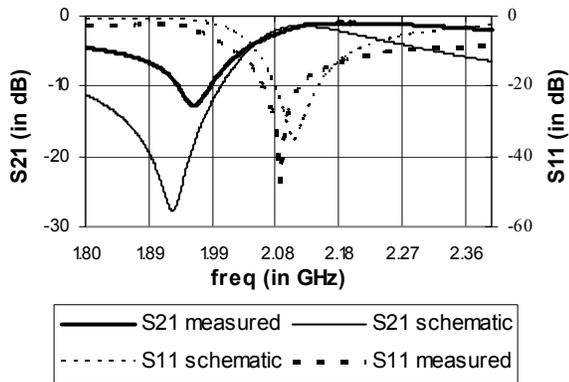Fig. 8. Die images of the SPSZ filter (left) and the three pole filter.

Fig. 9. Simulated and measured scattering parameters of single-pole single-zero filter.

The TX suppression is better than 10dB across the entire WCDMA TX band of 1920-1980MHz. This design uses only two MIM capacitors and occupies 468 µm x 246 µm on chip.

The three-pole filter has a higher measured insertion loss of 8dB at 2.3GHz, but the TX suppression is higher ~25dB at 2.1GHz (Fig. 10, the filter can be re-tuned to center at of the RX band at 2140MHz). The chip area is 917 µm x 414 µm.
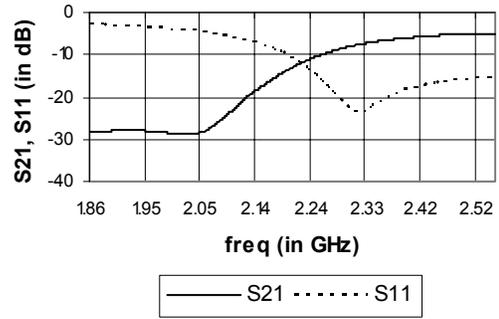

Fig. 10. Measured scattering parameters of 3-section filter.

V. CONCLUSION

Passive filters based on grounded bond wire inductance represent an attractive approach for a variety of modest performance RF applications, traditionally addressed by SAW filters and on-chip spiral inductors. They exhibit excellent Q, require small die area, and can be tunable using on-chip varactor diodes.

REFERENCES

[1] V. Aparin and L. Larson, "Analysis and reduction of cross-modulation distortion in CDMA receivers", *IEEE Trans. on Microwave Theory and Tech.*, vol. 51, no. 5, 1591-1602, May 2003.

[2] D. Li, and Y. Tsividis, "A 1.9GHz Si Active LC Filter with On-Chip Automatic Tuning", *2001 IEEE ISSCC Int. Solid-State Circuits Conf. Dig.*, pp. 368-369, Feb. 2001.

[3] M.A.L. Mostafa, J. Schlang, S. Lazar, "On-chip RF filters using bond wire inductors", *14th Annual IEEE Int. ASIC/SOC Conf. Proc.*, pp. 98-102, Sept. 2001.

[4] A. Dec, K. Suyama, "Microwave MEMS-based voltage-controlled oscillators", *IEEE Trans. on Microwave Theory and Tech.*, vol. 48, issue 11, part 1, pp. 1943-1949, Nov. 2000.

[5] 3GPP, "Terminal Conformance Specification; Radio Transmission and Reception (FDD) (Release 1999)," *Technical Specification 34.121*, vol. 3.4.0, March 2001.

[6] O.K. Jensen, T.E. Kolding, C.R. Iversen, S. Laursen, R.V. Reynisson, J.H. Mikkelsen, E. Pedersen, M.B. Jenner, and T. Larsen, "RF Receiver Requirements for 3G W-CDMA Mobile Equipment", *Microwave J.*, vol. 43, no. 2, pp. 22-46, Feb. 2000.