Compact lowpass ladder filters using tapped coils

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Abstract— Compact passive LC ladder lowpass filters for pulse shaping are realized using a single inductor with multiple taps. Mutual coupling between different inductors in a ladder results in zeros on the real and imaginary axis and can cause an undershoot in the step response and reduced attenuation in the stopband. Techniques to mitigate these effects are described. A seventh order Bessel filter is realized using the proposed technique in a $0.18\,\mu m$ CMOS process. This filter exhibits an undershoot of 1.3% and provides a stopband attenuation of $37\,\mathrm{dB}$. It occupies $0.048\,\mathrm{mm}^2$, which is at least 15% smaller than a realization with separate spirals for each inductor.
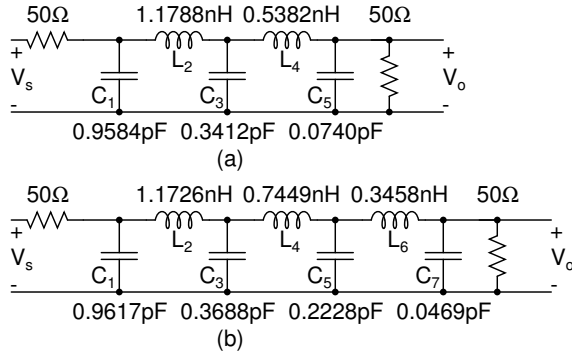
I. Motivation

Fig. 1.   7.5 GHz bandwidth Bessel filters for pulse shaping 10 Gb/s data

On chip LC lowpass ladder filters are used for realization of pulse shaping filters in broadband communication systems[1] and delay lines in equalizers[2]. Pulse shaping filters are used in broadband communications systems for limiting rise times of pulses and eliminating high frequency noise. These filters usually have a 3 dB bandwidth that is 75% of the data rate[1], [3]. Fig. 1 shows fifth and seventh order LC ladder Bessel filters for pulse shaping 10 Gb/s data. Conventional implementations of these filters on an integrated circuit, such as the one in [1] require a large area as the inductors have to be laid out sufficiently far from each other to avoid coupling.

The inductors in a lowpass LC ladder filter form a chain and can also be thought of as a single inductor with multiple taps. Realizing separate coils for a number of inductors occupies a larger area than realizing the total inductance using a single coil. This is due to positive mutual coupling between different parts of the coil. Since inductors are usually the largest components on integrated circuits, significant chip area can be saved by using a single inductor with multiple taps instead of separate inductors which need to be laid out far from each other. On the other hand, with a single tapped coil, mutual coupling between different inductors causes deviations in the pulse response and the frequency response which need to be corrected.

In the next section, we compare a single inductor with multiple taps to multiple spirals. In section III we analyze the effect of coupling between different inductors in a ladder filter. Section IV deals with techniques to restore the pulse response of the filter to the ideal one in presence of mutual coupling. Example realization of a Bessel filter using the proposed techniques are shown in section V. Detailed simulation results are shown in section VI.
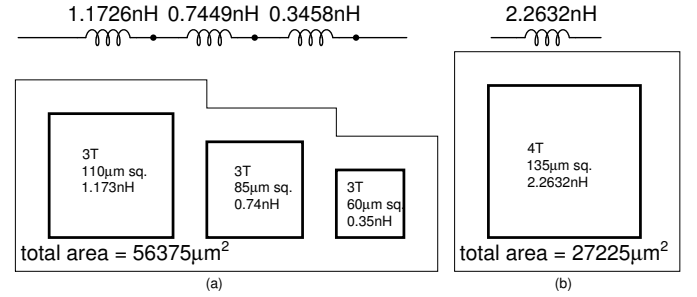
II. Single inductor with multiple taps

Fig. 2.   Inductors in Fig. 1(b): (a) separate spirals, (b) single spiral (Square spirals, $6\,\mu m$ wide metal lines, $5\,\mu m$ inter-turn spacing, $30\,\mu m$ clearance between and around inductors.)

Fig. 2(a) shows a simplified layout of the three inductors used for the filter in Fig. 1(b). Fig. 2(b) shows the total inductance (2.26 nH) realized using a single spiral with the same metal width and spacing as in Fig. 2(a). The area occupied by the single inductor is less than half the area occupied by the three inductors[1].

Realizing the total inductance as a single spiral results in mutual coupling between different coils. For on chip spirals, the coupling coefficient between turns is 0.6 or less.

III. Effect of coupling between inductors in a ladder filter

When the total inductance in a ladder is laid out as a single spiral, there will be mutual coupling between different inductors. This coupling is highest for adjacent inductors and reduces as one goes down the ladder. The coupling between adjacent coils and alternate coils are analyzed below.

The transfer function of the fifth order filter (Fig. 3(a)) with a mutual inductance $M_{24} = k_{24}\sqrt{L_2 L_4}$ between adjacent

[1]After this paper was accepted to *ISCAS*, the author became aware of [4] which describes the same idea. This work was done independently of [4] and references therein.
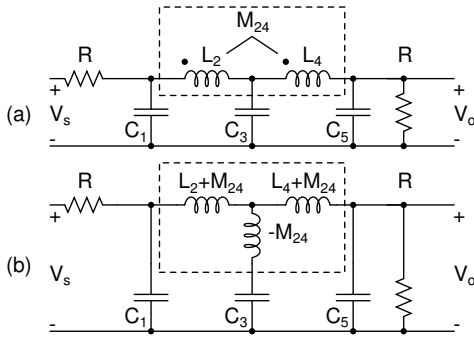
Fig. 3. (a) Fifth order ladder filter with coupling between adjacent inductors, (b) Equivalent circuit with uncoupled inductors

inductors L_2 and L_4 is given by

$$\frac{V_o(s)}{V_s(s)} = \frac{1 - s^2 M_{24} C_3}{D_5(s)} \tag{1}$$

where $D_5(s)$ is a fifth order polynomial in s. Because of mutual coupling between adjacent coils, real zeros are introduced at $\pm\sqrt{1/M_{24}C_3}$. These zeros cause an undershoot in the pulse response and a reduced attenuation in the stopband. This effect can also be seen by using the well known representation of two coupled coils in series using three uncoupled coils (Fig. 3(b)). The series resonance of C_3 with the negative inductance $-M_{24}$ creates "notches", i.e. zeros, on the real axis of the s plane. In higher order filters, a pair of symmetric zeros are created on the real axis for every pair of adjacent coupled inductors.
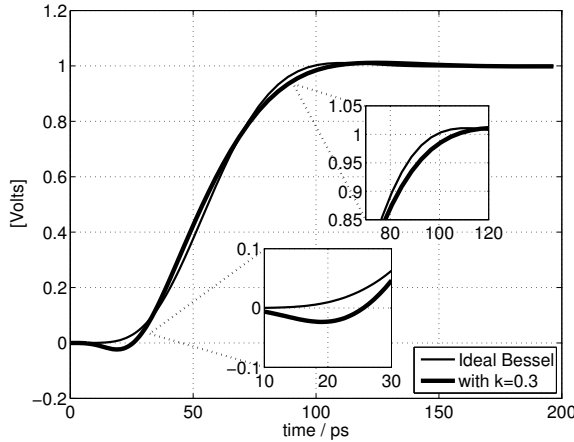

Fig. 4. Step response with and without mutual coupling

To assess the effect of coupling between adjacent inductors, the filter in Fig. 3(a) is simulated with different coupling coefficients between the inductors L_2 and L_4. In each case, the effective inductance values $L_2 + M_{24}$ and $L_4 + M_{24}$ are adjusted to the desired inductance values shown in Fig 1(a). This is equivalent to simulating the ideal Bessel ladder filter with uncoupled inductors and an extra negative inductance $-M_{24}$ in series with C_3. Fig. 4 and Fig. 5 compare the step response and the frequency response for $k_{24} = 0$ and $k_{24} = 0.3$. The step response exhibits an undershoot and a slower rise than the ideal response. Fig. 6 shows the undershoot in the step response of 5th and 7th order Bessel filters as a function of
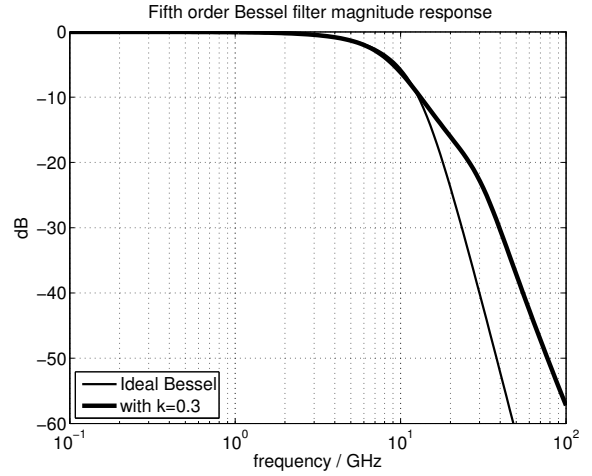

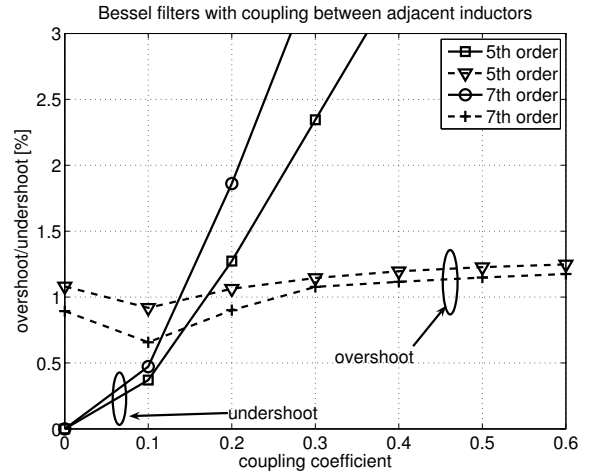Fig. 5. Magnitude response (normalized to dc gain)

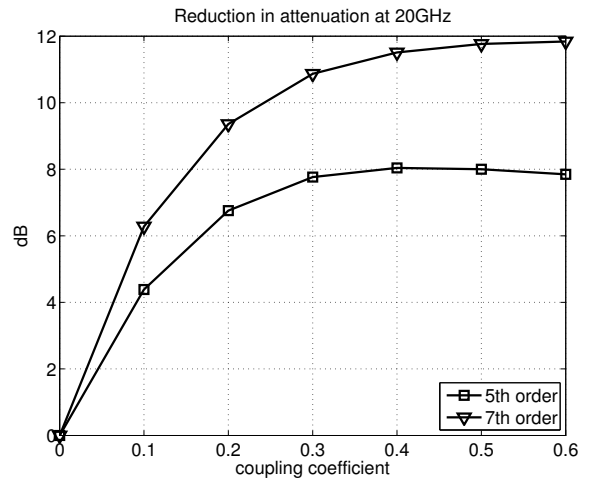Fig. 6. Undershoot due to mutual coupling

Fig. 7. Degradation of attenuation at 20 GHz due to mutual coupling

the coupling coefficient. Fig. 7(b) shows the degradation in the attenuation of these filters at 20 GHz. This is representative of the stopband attenuation.

In filters with three or more inductors, there will also

be mutual coupling between inductors that are not adjacent to each other. Consider the seventh order ladder filter in Fig. 1(b) with a mutual inductance $M_{26} = k_{26}\sqrt{L_2 L_6}$ between L_2 and L_6. Its transfer function is given by

$$\frac{V_o(s)}{V_s(s)} = \frac{1 - s^2(C_3 + C_5)M_{26} - s^4 C_3 C_5 L_4 M_{26}}{D_7(s)} \qquad (2)$$

where $D_7(s)$ is a seventh order polynomial in s. Two pairs of zeros are created, one on the real axis and one on the imaginary axis. The imaginary axis zeros will be at a higher frequency than the real axis zeros. The effect of real axis zeros is as described earlier. The imaginary axis zeros create a notch in the frequency response. Because of the zeros, the attenuation in the stopband will be reduced. As alternate inductors couple more weakly than adjacent inductors, the zeros due to the former can be expected to be at higher frequencies than those due to the latter.

IV. REDUCING THE EFFECT OF COUPLING

If the coupling is small, its effect can be ignored in certain applications. For instance, assume that a fifth order Bessel filter is used for pulse shaping. The step response of an ideal fifth order Bessel filter has an overshoot of about 1.1% (Fig. 6, $k = 0$). An undershoot of the same magnitude can therefore be reasonably be permitted without undermining the pulse shaping function. This indicates that, if the coupling coefficient is less than 0.2, the filter with coupled inductors can be used without modifications for pulse shaping.

In many cases, the coupling between alternate inductors (L_2 and L_6) is small enough to be ignored but coupling between adjacent inductors is not. A technique to eliminate the effect of coupling between adjacent coils is described below.
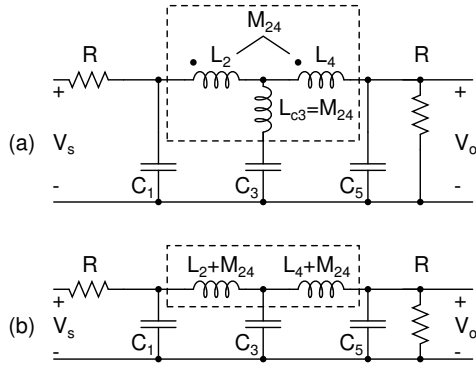

Fig. 8.   Cancelling the effect of coupling between adjacent inductors

As shown in Fig. 3(b), two coupled inductors with one common node can be represented using two uncoupled inductors and a negative inductance connected to the common node. To cancel the effect of coupling, a positive inductor can be connected in series with the branch containing the series inductor as shown in Fig. 8(a). When the positive inductance exactly cancels the negative inductance, the circuit reduces to the one shown in Fig. 8(b) and the zeros (Eq. 1) disappear. Even if the cancellation is not exact, the zeros will be moved to higher frequencies on the real axis (if the net inductance

is negative) or on the imaginary axis (if the net inductance is positive) of the s plane. As a result, the degradation in high frequency attenuation and the undershoot or other deviations in the pulse response will be reduced.

In practice, when the mutual inductance to be cancelled is small (a few tenths of a nanohenry), it is not necessary to explicitly implement the positive inductance used for cancellation. The capacitor C_3 in Fig. 8 is connected to the inductor somewhere along the spiral. The starting and ending nodes of the spiral will be close to each other near the periphery. The inductance of the interconnect used to connect C_3 to a tap along the spiral helps cancel the negative inductance. To minimize coupling between the main spiral and the compensating inductance L_{c3}, the interconnect can be routed along the centerlines of the square spiral as much as possible.
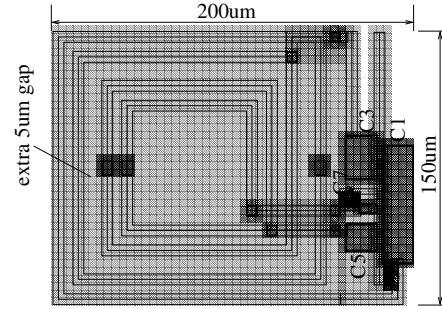
V. SEVENTH ORDER BESSEL FILTER REALIZATION

Fig. 9.   Layout of the seventh order Bessel filter

Fig. 9 shows the layout of a seventh order Bessel filter in a $0.18\,\mu$m CMOS process. The spiral is wound using $2.06\,\mu$m thick top level metal layer with a $6\,\mu$m width and $5\,\mu$m spacing between turns. An extra $5\,\mu$m gap is left after the first tap to reduce the coupling coefficient to about 0.3. The capacitors used are metal-metal capacitors. Simulation and optimization of the inductor are carried out using Fasthenry[5]. The desired and obtained inductances between taps and coupling coefficients are shown in Table I. The obtained coupling coefficients are close to the assumed values. The interconnect inductance in series with C_3 is much smaller than the desired value for compensation. Therefore, residual undershoot can be expected in this filter. With a clearance of $30\,\mu$m on three sides, this filter occupies $48,300\,\mu$m^2, which is about 15% smaller than the placement area of three separate spirals in Fig. 2(a).

Fig. 2(a) does not show the complete layout. Interconnects and capacitors will occupy additional space. Therefore area saved using the proposed technique is expected to be more than 15%.

TABLE I
SIMULATED PARAMETERS OF THE SPIRAL IN FIG. 9

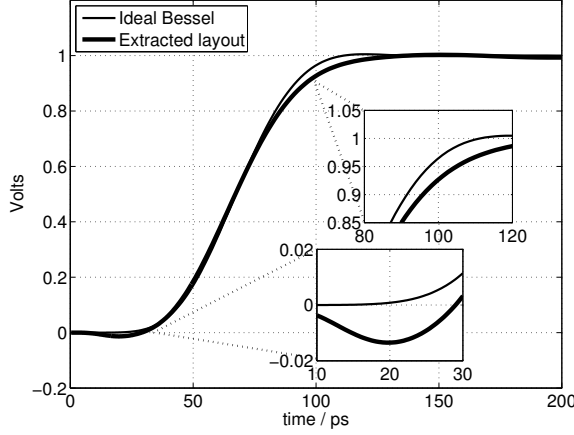|	Desired	Obtained		Desired	Obtained
L_2	0.9992 nH	0.957 nH	k_{24}	0.3	0.308
L_4	0.3586 nH	0.424 nH	k_{46}	0.3	0.339
L_6	0.1796 nH	0.187 nH	k_{26}	0	0.160
L_{c3}	180 pH	96 pH	L_{c5}	76 pH	24 pH

VI. SIMULATED RESULTS

Fig. 10.   Step response of ideal and realized seventh order Bessel filters
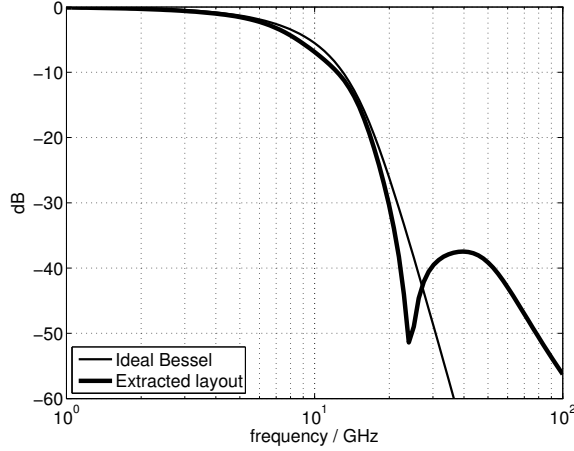

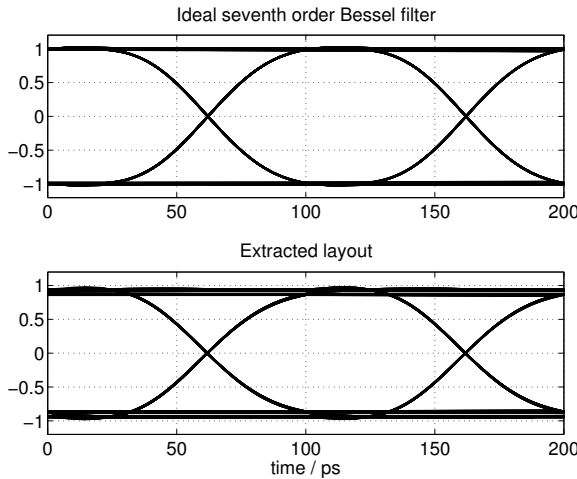Fig. 11.   Magnitude response of ideal and realized seventh order Bessel filters

Fig. 12.   Output eye diagrams with 10Gb/s data

The filter in Fig. 9 is simulated including all the inductances, parasitic capacitances, and series resistances. The inductance of the spiral, the tap connections, and the ground line and the coupling coefficients between them are simulated using Fasthenry. The parasitic capacitances and resistances are extracted from the layout. The resulting circuit is simulated in the time and frequency domains. The realized filter has an additional loss due to series resistance of the spiral. For clarity, the pulse and frequency responses are normalized to the dc gain of the filter.

Fig. 10 shows the step response of the filter. It shows an undershoot of 1.3% and an overshoot of 0.3%. The residual undershoot and the slowing down in the step response is due to the still uncompensated zero caused mainly by mutual inductance between L_2 and L_4. Fig. 11 shows the frequency response of the filter. The magnitude error is very small in the passband. The filter provides a high frequency attenuation better than 37 dB. There is a notch in the magnitude response. This is due to parasitic capacitances between the turns of the inductor which create parallel LC branches in the ladder.

Fig. 12 shows the eye diagrams at the output of the ideal and the realized filters. The output eye from the realized filter has a slightly greater closure and asymmetry.

VII. CONCLUSIONS

A single spiral with multiple taps can be used to realize lowpass LC ladder filters with a reduced area. Use of a single spiral results in mutual coupling between inductors of the ladder. Coupling between adjacent inductors creates a pair of symmetric zeros on the real axis and coupling between alternate inductors creates two pairs of symmetric zeros on the real and imaginary axes. The real axis zeros due to coupling between adjacent coils can be eliminated using inductors in series with the capacitors. In practice, the interconnect inductance from the taps along the spiral to the capacitors can be used to to eliminate the zeros or to move them to higher frequencies, thus realizing a better approximation to the desired transfer function.

The proposed techniques also benefit conventional ladder filter realizations with uncoupled inductors. The inductors can be moved closer to each other and the effect of resultant coupling can be eliminated using inductors in series with the capacitors. These techniques are also applicable to filters using spirals on a printed circuit board.

Since inductors occupy a large area and require large gaps to reduce mutual coupling to negligible levels, using a single spiral or moving the spirals closer result in significant area savings.

REFERENCES

[1] A. Boulouard et al., "Wide-band GaAs MMIC low-pass filters," *Gallium Arsenide Applications Symposium, GAAS 1994*, 28-30 April 1994, Italy.
[2] Hui Wu et al., "Integrated transversal equalizers in high-speed fiber-optic systems," *IEEE Journal of Solid State Circuits*, pp. 2131-2137, vol. 38, issue 12, Dec. 2003.
[3] "Standard and Customs Bessel Filters" from *Nanowave technologies*, http://www.nanowavetech.com/prod_rf_components.htm
[4] T. Ito, K. Okada, K. Masu, "Characterization of On-Chip Multi-Port Inductors for Small-Area RF Circuits", *IEEE Transactions on Circuits and Systems I: Regular Papers*, Accepted for future publication.
[5] "Fasthenry: A multipole accelerated field solver", http://www.rle.mit.edu/cpg/research_codes.htm