Electronically tunable allpass filter: linear VCO design

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Abstract: A new electronically tunable allpass filter (ETAF) realization using the composite Current Feedback Amplifier (CFA) and Multiplication Mode Current Conveyor (MMCC) building blocks is proposed. First order non-minimum phase function with electronically variable output phase is derived. Extension of the filter to a linear quadrature-VCO design is then implemented. Simulation test responses of all these functions are satisfactorily verified.

Keywords: allpass (AP) function, linear VCO, MMCC, electronically tunable phase equalizer

Classification: Integrated circuits

References

[1] R. Genin: Proc. IEEE \textbf{56} (1968) 1746. DOI:10.1109/PROC.1968.6731
[2] M. Higashimura and Y. Fukui: IEEE Trans. Circ. Syst. \textbf{37} (1990) 660. DOI: 10.1109/31.55015
[3] R. Nandi: IEEE Trans. Instrum. Meas. \textbf{41} (1992) 553. DOI:10.1109/19.155925
[4] N. Pandey, R. Pandey and S. K. Paul: J. Electron. Devices \textbf{12} (2012) 772.
[5] S. Maheshwar and B. Chauhan: IET Circ. Dev. Sys. \textbf{6} (2012) 103. DOI: 10.1049/iet-cds.2011.0213
[6] A. Toker and S. Ozoguz: Int. J. Electron. Commun. (AEU) \textbf{58} (2004) 153. DOI:10.1078/1434-8411-54100221
[7] D. Biolek and V. Biolkova: Electron. Lett. \textbf{45} (2009) 807. DOI:10.1049/el.2009.0575
[8] J. W. Horng, C. L. Hou, C. M. Chang, Y. T. Lin, I. C. Shiu and W. Y. Chiu: Int. J. Electron. \textbf{93} (2006) 457. DOI:10.1080/00207210600711481
[9] D. Biolek and V. Biolkova: Analog Integr. Circ. Sig. Proc. \textbf{65} (2010) 123. DOI:10.1007/s10470-009-9435-2
[10] N. Herencsar, S. Minai, J. Koton, E. Yuce and K. Vrba: Analog Integr. Circ. Sig. Proc. \textbf{74} (2013) 141. DOI:10.1007/s10470-012-9936-2
[11] T. Tsukutani, H. Tsunetsugu, Y. Sumi and N. Yabuki: Int. J. Electron. \textbf{97} (2010) 285. DOI:10.1080/00207210903289409
[12] S. Oztayfun, S. Kilinc, A. Celebi and U. Cam: Int. J. Electron. Commun. (AEU) \textbf{62} (2008) 228. DOI:10.1016/j.ijecomp.2007.03.012
[13] Y. S. Hwang, W. H. Liu and J. J. Chen: Proc. IEE-IET Circuits, Dev. Syst. 3
Realization of several variants of AP filters had been reported in the recent past following the appearance of various types of active building blocks, e.g., voltage op-amp [1], current conveyor [2, 3], DVCCTA [4], DXCCII [5], DDA [6], CITA [7], DDCC [8], VD-DIBA [9], VDIBA [10], DVCC with OTA [11] and DO-CCC [12]. Albeit most of these designs are passive tuned, only few versions of electronically tunable topologies are also reported recently [10, 11, 12]. These designs use bias current (I_b) control of trans-conductance (g_m) tuning of OTA type devices for phase variation; this approach requires additional current processing hardware and involvement of thermal voltage (V_T). Here we utilize the relatively new MMCC element [13] coupled with a readily available CFA device as a composite building block for the ETAF design that provides direct variation of the phase by the control voltage (V) of the MMCC element. Such composite building block configuration
approach were used in some previous work, viz., DVCC with OTA [11], OTA with unity-gain difference amplifier (UGDA) [9], OTA with inverting voltage buffer VDIBA [10] and MMCC with DVCCTA based synthetic-L [14] and MMCC-CFA based dual-input integrator; in [14] phase tuning is upto 200 KHz and in the latter, range is upto 1.8 MHz. Present work is also of composite MMCC-CFA building block category wherein we obtained better performance with respect to frequency-range at low THD. Literature suggests that a composite structure of active devices may yield better flexibility and design versatility that a single constituent unit may not provide [15].

Here we propose a first order ETAF function using a single grounded RC-section in which the phase (θ) is tunable simply by adjustment of the MMCC control voltage (V). Design extension of this stage by cascade with an inverting integrator is then presented to implement a QVCO with linear tuning law. It is shown that effects of device port mismatch error (|e| ≪ 1) and parasitic components are insignificant. The proposed designs are experimentally verified by PSPICE simulation and hardware tests.

2 Analysis

The ETAF topology is shown in Fig. 1(a); the device nodal relations are \( I_z = α_{x(1,2)}I_x \), \( V_x = β_{y(1,2)}kV \), \( k = \alpha \) multiphase constant = \( 0.1/\text{volts} \) [16] and \( V_o = δ_{z(1,2)}V_x \); subscript-l is for MMCC and 2 for CFA (without \( kV \)). Ideally the port transfer ratios are unity but may be considered to have a single-pole frequency roll-off given by \( α_s ≈ \alpha_o/(sr_1 + 1) \), \( β_s ≈ \beta_o/((sr_o + 1) \) and \( δ_s ≈ \delta_o/((sr_2) + 1) \). These pole frequencies are of the order of hundreds of MHz with the current technology [17]. Hence for frequency ranges of \( f < f_i,v,z \), we may write \( |α| ≈ (1 - e_i) \), \( |β| ≈ (1 - e_v) \) and \( |δ| ≈ (1 - e_o) \) where \( |e| (< 1) \) denote port mismatch error [17, 18].

Analysis of Fig. 1(a) yields the signal transfer relations as

\[
E_o = -[\dot{x}_aV_i/(\dot{x}_a + (Y_2/kV_y Y_1))] \quad \text{and} \quad -(V_o/\gamma_2) = (\alpha V_i + bE_o)
\]  

(1)

where \( \dot{x}_{a,b} = r_{a,b}/(r_a + r_b) \), \( a = r_0/r_1 \), \( b = r_0/r_2 \) and \( \gamma_1 = (\alpha \beta \delta)_{11} \approx (1 - e_{11}) \), \( \gamma_2 = (\alpha \beta \delta)_{2} \approx (1 - e_{2}) \); \( e_{11} \approx e_1 + e_2 \), \( e_{2} \approx e_3 \). Initially we assume \( e = 0 \) and derive the transfer function with \( r_o = r_b \), \( a = r_0/r_1 = 1/2 \), \( b = r_0/r_2 = 1 \) and taking \( Y_2 = sC \), \( Y_1 = 1/R \), we get

\[
H(s) = \frac{1}{\frac{s}{2}} \frac{(1 - sr)/(1 + sr)}
\]

(2)

![Fig. 1.](image-url) (a) ETAF design topology (b) Integrator cascaded with (a) for QVCO design
which is a first order AP function with constant flat gain \( G_o = -6 \text{ dB} \) and phase \( \theta = -2 \text{arctg}(\omega r); \ r = 2 \text{ RC/kV} \). Thus electronic phase-variation may be obtained in a range \( 0 \leq \theta^o(\text{lag}) \leq \pi \). Active-sensitivities, if \( \epsilon \neq 0 \), are \( S' \approx \epsilon/(1 + \epsilon R) \ll 1 \) and \( S^{00} \approx \epsilon/(1 - \epsilon R) \ll 1 \).

Effects of the shunt-\( r_p C_p \) parasitics of the MMCC-stage may be expressed by a modified transfer

\[
\hat{H} = \frac{1}{2} \left\{ (1 - p) - sr' \right\} / \left\{ (1 + p) + sr' \right\}
\]

(3)

where

\[
r'/r = (1 + \mu); \ \mu = C_{p1}/C \ll 1; \ p = R/kVr_p \ll 1
\]

Parasitic component values [19] are in the range \( 2 \text{ M}\Omega \leq r_p \leq 5 \text{ M}\Omega \) and \( 3 \text{ pF} \leq C_p \leq 6 \text{ pF} \) while nominal RC components used are of K\( \Omega \) and few hundred pF order. Since capacitor \( C \) and \( C_p \) are both grounded, values of \( C_p \) may be pre-absorbed in \( C \) for the design. Effect of the \( C_p \) in CFA stage is neglected since the pole it creates with shunt \( r_o \) (\( \approx 1 \text{ K}\Omega \) say) lies at about 40 MHz as per our value of \( C_p \approx 4.2 \text{ pF} \) (measured). Albeit output phase is slightly changed due to the parasitics thereby causing some phase error (\( \theta_p \)), the allpass property remains practically unaltered since \( p \ll 1 \) as seen in (3).

3 Effect of poles of port-tracking ratios

The device port tracking ratios may be expressed by a single pole model, given by

\[
a_{1,2} = a_{o1,2}/(1 + sr_{1,2}); \ \beta = \beta_{o1,2}/(1 + sr_{v1,2}); \ \delta = \delta_{o1,2}/(1 + sr_{v2,2}) \quad \text{where subscript-1 is for MMCC and 2 for CFA in Fig. 1; re-analysis then yields}
\]

\[
H = \frac{1}{2} \left\{ \frac{a_{o2}\delta_{o2}}{(1 + sr_{12})(1 + sr_{v2})} \right\} \frac{\text{str}(s) - a_{o1}\beta_{o1}\delta_{o1}}{\text{str}(s) + a_{o1}\beta_{o1}\delta_{o1}}
\]

(4)

where \( F(s) = (r_1 r_v r_2) s^3 + \{ r_2 r_v r_3 + r_3 r_2 + r_1 r_v \} s^2 + (r_1 + r_v + r_2) s + 1 \).

Examination of the denominator of eq. (4) through Routh-Hurwitz criterion reveals that the proposed filter design is stable as \( r_{(v,v,2)} \ll r \).

4 Linear QVCO

Finally a linear Quadrature VCO design is derived by cascading the first order ETAF in Fig. 1(a) with an [14] inverting integrator \( G(s) \) of Fig. 1(b); given by

\[
v_o/v_1 \equiv G(s) = -1/(sr_o + \rho)
\]

(5)

where \( r_o = R_o C_o (1 + \sigma)/kV; \ \rho = R_o/(kVr_p) \ll 1 \) and \( \sigma = C_{p2}/C_o \ll 1 \). The design of the VCO is derived from the regenerative loop equation \( \{1 - G(s)H(s)\} \equiv 0 \), which yields the characteristic equation

\[
2s^2 r_o + s(2r_o - \tau(1 - 2p)) + 1 + 2p = 0
\]

(6)

Equating the imaginary and real parts in (6) to zero one gets

- Realizability condition: \( r_o/\tau = (1 + \mu)/(1 + \sigma)(1 + p) \approx 1 \) i.e., \( RC \approx R_o C_o \)
- Oscillation frequency: \( \omega_o = kV\sqrt{(1 + 2p)/(2RC)} \approx \sqrt{V/20RC} \)

Hence a QVCO with linear tuning law followed by control voltage (V)-tuning is realized. The above two adjustments are independent. The experimental results of the proposed design are shown in Fig. 2.
Literature study indicates that AP-filter based passive-tuned \([20, 21(\text{multiphase type})]\) oscillators were reported in the past. A relevant comparative summary to this extent is presented in Table I. It may be seen that albeit electronically tuned QVCOs are also proposed earlier \([10, 26, 27, 28, 29, 30, 31, 32]\), but such an oscillator based on electronically tunable AP filters with linear tuning law had not yet been presented, as is seen by the comparative description in Table I below.

### Table I. Summary of some recent QOs

| Ref. | Device used | Electronic Tunability | Linear Law | \(f_o\)-range (KHz) | Tuning by | THD (%) |
|------|-------------|-----------------------|------------|---------------------|-----------|---------|
| [4]  | DVCCTA      | Yes                   | No         | 1590                | \(\sqrt{I_b}\) | x       |
| [10] | VDIBA       | Yes                   | No         | 8500                | \(\sqrt{I_b}\) | 2.25    |
| [21] | VOA         | No                    | No         | 22.9                | RC        | <0.1    |
| [22] | VOA         | No                    | No         | 160                 | RC        | x       |
| [23] | CFOA        | No                    | No         | 159                 | RC        | 3.16    |
| [24] | CDBA        | No                    | No         | 16                  | RC        | 1.94    |
| [25] | DDCC        | No                    | No         | 1060                | RC        | x       |
| [26] | OTA         | Yes                   | Yes        | 64                  | \(I_b\)   | x       |
| [27] | DVCCTA      | Yes                   | No         | 3183                | \(I_b\)   | x       |
| [28] | CDTA        | Yes                   | No         | 1730                | \(\sqrt{I_b}\) | x |
| [29] | CCCDBA      | Yes                   | No         | 420                 | \(\sqrt{I_b}\) | 2.0 |
| [30] | CCCCTA      | Yes                   | Yes        | 1100                | \(\sqrt{I_b}\) | 1.1~2.9 |
| [31] | CCCCTA      | Yes                   | Yes        | 1000                | \(I_b\)   | 1.24 |
| [32] | CFA-MMCC    | Yes                   | Yes        | 1800                | V         | 2.1     |

- QO-designs based on AP filter but not linear law: [4]-electronic tuning; [23]-passive tuning
- Electronically-tunable linear designs using: double-integrator loop \([29] \& [32]\); Wien-network \([31]\)
- Proposed: only design based on AP filter with electronic-tuning and linear-law

## 5 Experimental results

Measured responses of ETAF and QVCO are shown in Fig. 2; error \(\theta_e\) was seen to be small for the ETAF while the THD-level (upto 7th harmonic) for both ETAF and
QVCO is quite low compared to [10, 29, 30, 32]. Tuning error in Table II is measured up to 3.3 MHz by a new method here by evaluating the phase margin of the loop at gain-crossover frequency.

### 6 Conclusion

A new first-order ETAF realization is proposed which had been subsequently extended to derive a linear QVCO with an inverting integrator looped around it. Experimental results indicate insignificant effects of parasitic, low $\theta_e$, THD and oscillation tuning error ($\beta$). In the same proposed ETAF topology a second-order function may be implemented if $Y_2$ is replaced by a series-LC resonator, as in [14]; appropriate response of this design had also been verified.

#### Table II. Measurement of Tuning error ($\beta$) and THD of QVCO response

| Curve | $f_0$ (MHz) | $\mu_{0,\text{dB}}$ | $\Delta f$ (KHz) | $\beta\%$ | THD (%) |
|-------|-------------|-----------------|-----------------|--------|--------|
| A     | 0.5         | 0.988           | 6               | 1.2    | 0.95   |
| B     | 1           | 0.975           | 25              | 2.5    | 1.10   |
| C     | 3.3         | 0.965           | 115             | 3.5    | 1.23   |

QVCO is quite low compared to [10, 29, 30, 32]. Tuning error in Table II is measured up to 3.3 MHz by a new method here by evaluating the phase margin of the loop at gain-crossover frequency.