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Key Parts for Ultra-Low-Noise Synthesizer Design

The focus in this article is on the key parts needed for ultra-low-noise synthesizer design like crystal references, power supplies, and low-noise op amps.

Welcome to Part 4 of this 5-part series on ultra-low-noise synthesizer design. Part 1 introduced advanced loop design and included both passive and active filters. Part 2 covered noise sources in the loop outside of the synthesizer integrated circuit (IC). Part 3 added synthesizer IC noises and how they are modeled, as well as how all of the noise sources are combined and shaped by the loop.

This article covers the key parts required by design engineers seeking the lowest-noise designs, or lowest noise for a particular cost. Since the designer is naturally concerned with the cost tradeoffs of these key parts, that information is presented in some detail here. Additional information is available in the long version posted on the Longwing Technology website (www.longwingtech.com). Part 5 will bring it all together in the form of low-noise examples, comparing and contrasting the performance attained by the various methods and the available parts.

Key Components

Major Trends

The most significant trend driving lower noise in modern single-loop synthesizers is the development of the delta-sigma synthesizer IC in very high-speed IC processes. This synthesizer approach allows for fractional-N synthesis with real number multiplication of the reference frequency. A key breakthrough is that high fractional resolution allows for high-frequency references. This, in turn, enables high bandwidth for maximum noise suppression inside a much wider loop bandwidth than integer synthesizers allow for, i.e., bandwidths may now exceed 400 kHz.

Another important factor is associated with using multiple voltage-controlled oscillators (VCOs) on die combined with hundreds of narrowband resonators (Ref. 5). In this scenario, which emulates wideband VCOs to hit any frequency by use of frequency division, the on-die noise performance past the loop bandwidth in offset and above about 4 GHz in VCO frequency can generally match or beat the best octave-bandwidth discrete VCOs.

The best octave-bandwidth VCOs below 4 GHz can currently outperform on-die narrowband emulations of wideband VCOs by about 2 to 8 dB, while the best narrowband VCOs can exceed on-die performance by 10 to 30 dB. It's thus mostly in the narrowband VCO case, and in applications in which noise past the loop bandwidth of typically about 50 to 400 kHz is critical, where discrete VCOs still find success.

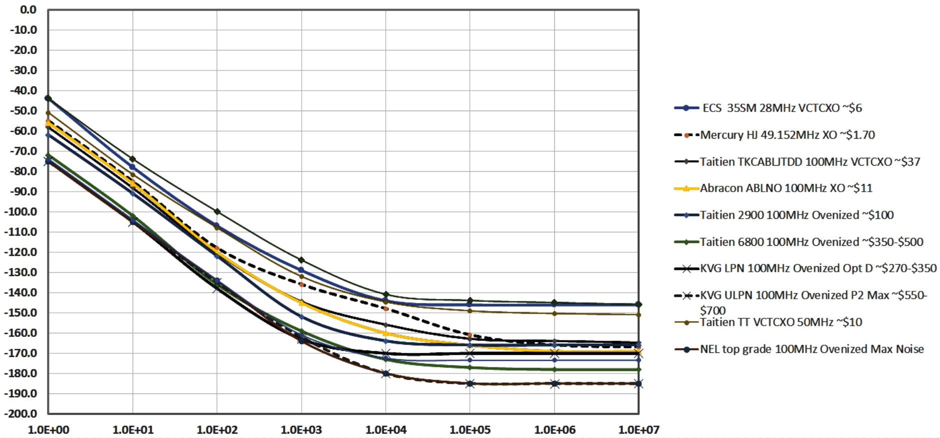
Integer-N synthesizer crystal references in the past were usually in the range of 1 to 20 MHz (10 MHz being a popular choice), with divided frequency steps typically in the range of 1 to 200 kHz as per system requirements. However, the capability of the fractional-N synthesizer to effectively hit any frequency with only small error allows for the use of higher-frequency references.

Crystal oscillators as high as 100 MHz are now becoming available at cost-effective prices, and many synthesizers enable internal doubling to 200 MHz to allow for even higher loop bandwidths. The need to support ultra-low-noise VCOs and crystal oscillators also led to lower-noise voltage regulators to supply them.

Synthesizer ICs

Among the key issues associated with choosing modern delta-sigma synthesizers are internal noise parameters, which model the noise that the charge pump and dividers induce on the VCO in the closed-loop state. These are further described in the long form of this article, and in still more detail in Part 3 of this series (Ref. 3). The parameters are modeled as a flat and 1/f noise term for each part.

When using a device in fractional mode, the in-band phase noise may be slightly degraded, depending on the fraction and



1. Shown are example phase noises for crystal oscillators displaying excellent noise performance. These commercially available parts operate from 28 to 100 MHz; here, they are normalized to 100-MHz noise performance for fair comparison.

how it's expressed. This fractional noise floor appears to add to the integer noise floor modeled by the term PN1Hz. Some manufacturers, such as Analog Devices (ADI) (www.analog.com), may account for this by increasing PN1Hz by a modest amount, which may be 1 to 3 dB in fractional mode.

In Part 3, a figure of merit combining the noises of the flat and 1/f terms is developed. Results of this combination are shown in *Table 1*. This figure of merit is proportional to synthesizer-chip-induced noise power from 1 Hz to a bandwidth of f_L. Therefore, smaller is better.

Crystal References

In the case of the modern delta-sigma, fractional-N, high-

TABLE 1: SYNTHESIZER ICs

Part	Freq range	On-die VCO	Norm phase-noise floor and flicker in dB, and total noise figure of merit	Price	Comments
TI LMX2491	500 MHz to 6.4 GHz	No, only ext	–227 floor dB –260 flicker dB 1.35E-17 tot	$2.90 @1k	State of the art for the price. FMCW radar functions. Charge pump can tune to 5.25 V. The LTC6947 is a similar competitor, but about 2X the cost. The LMX2492 is a 14-GHz version for ~$8.75 @ 1k.
TI LMX2571	10 MHz to 1344 MHz Internal VCO, 100 MHz to 2 GHz External VCO	Yes, option for off-die	–231 floor –260 flicker 1.23E-17 tot	$5.50 @1k	State-of-the-art lower power synthesizer. Ext VCO to 2 GHz, but RF buffer output limited to 1400 MHz. This part is ideally architected for land mobile use.
TI LMX2572LP	12.5 MHz to 2 GHz	Yes	–232 floor –265.5 flicker 5.77E-18 tot	$6 @1k	State-of-the-art lower power, lower freq, lower cost synthesizer.
TI LMX2582	20 MHz to 5.5 GHz	Yes	–231 floor –266 flicker 3.67E-18	$9 @1k	State of the art for the price in a medium frequency. The LMX2592 is a 9.8-GHz version for $20.50 @ 1k.
TI LMX2594	10 MHz to 15 GHz	Yes	–236 floor –269 flicker 1.7E-18 tot	$42.50 @1k	State-of-the-art on-die VCO synth IC. The -235dBc/Hz normalized frac PLL noise is the lowest currently available. The LMX2595 is a 20-GHz version for $62.50 @ 1k.
Analog Devices ADF41513	1 GHz to 26.5 GHz	No, ext. only	–234 int floor –231 frac floor –267 flicker 3.09E-18 tot	~$30 @1k	State of the art for a high-frequency ext. VCO synthesizer. The –231-dBc/Hz fractional normalized PLL noise is the lowest currently available for external VCOs.
Analog Devices ADF4372	62 MHz to 16 GHz	Yes	–234 int floor –233 frac floor –267 flicker 2.3E-18 tot	~$65 @1k	Near state of the art, though LMX2594 is a direct competitor with lower noise and cost. Typical spurious of –90 dBc. The ADF4371 is a 32-GHz version at ~$250 @ 1k.
Analog Devices ADF5610	57 MHz to 14.6 GHz	Yes	–232 int floor –229 frac floor –268 flicker 2.46E-18 tot	~$48 @ 1k	Near state of the art at a lower price than the ADF4372, with low typical spurs of –105 dBc, at the cost of about 4 dB higher in-band phase noise.

Listed are leading delta-sigma synthesizer ICs. Lower noise is more expensive, but lower noise combined with higher frequency is what really counts. Note: Texas Instruments reports no difference in broadband phase noise between integer and fractional mode, though spurs may vary. Analog Devices typically reports a difference in integer and fractional mode normalized noise, in which fractional is about 1 to 3 dB noisier.

bandwidth synthesizer, the crystal reference oscillator is the component that can often be the most expensive and have the greatest impact in the system. Phase noise is considered at offsets from the carrier on a per-Hz basis. Inside the loop bandwidth, there will typically be a range of frequencies in which the synthesizer-chip noise parameters set the phase-noise floor, as well as a lower range of frequencies in which the multiplied crystal oscillator noise is dominant over the chip noise. Understanding the tradeoffs here can significantly affect the total cost.

Figure 1 shows the phase-noise performance of a set of commercially available crystal reference oscillators that, under different conditions, are all well-suited for modern usage. Though these are all low-noise oscillators for their price, there's a phase-noise variation of approximately 30 to 40 dB. Even more striking is the price variation, which varies from less than $2 to over $1,000.

For decades, 10 MHz was the standard frequency of the finest low-noise crystal oscillators. However, 100 MHz is rapidly becoming a new standard for this application, with both voltage-controlled temperature-compensated crystal oscillators (VCTCXOs) and ovenized oscillators now available. Lower-cost simple crystal oscillators will typically have 10 to 100 parts per million (ppm) accuracy and temperature drift. This performance, if acceptable, can lead to quite good noise performance for prices ranging from less than $2 to about $12.

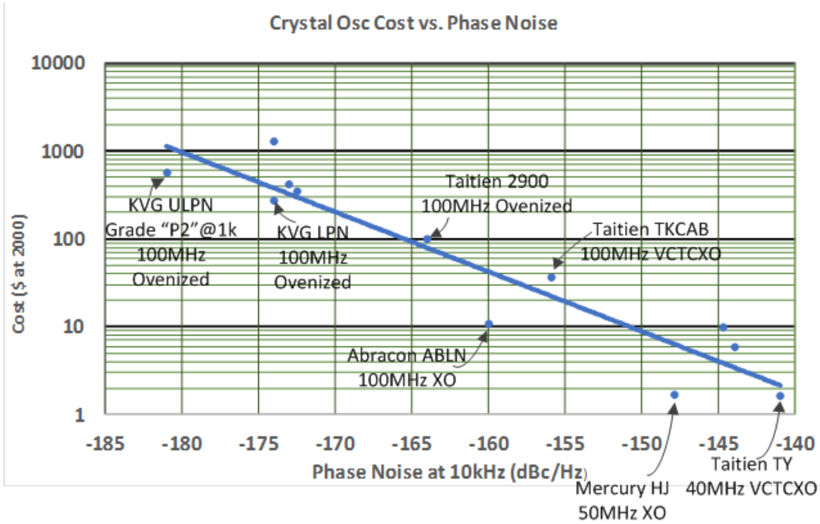
VCTCXOs offer frequency accuracy from about 0.5 to 2 ppm. VCTCXOs at frequencies under 40 MHz with phase noise suitable for wireless handsets (typically consuming less than 3 mA) are available for less than $2 and sometimes less than $1 in high volumes. At 40 MHz and with performance suitable for base stations, price ranges from about $4 to $8.

However, newly released VCTCXOs at 100 MHz (Taitien, www.taitien.com, TKCAB) that are ideal for the latest synthesizer ICs aimed at high-performance communications, wireless infrastructure, and test equipment are tending to be in the price range of $25 to $40. For the most demanding applications, ovenized oscillators at 100 MHz with initial frequency

TABLE 2: CRYSTAL REFERENCES

General requirements	Part	Freq	Accuracy and phase noise @ 1 kHz norm to 100 MHz	Typical cost	Comments
Low-cost VCTCXO	Taitien TY	40 MHz	±1 ppm –124dBc/Hz	~$0.80 to $1.80	Excellent performance for a low-cost handset class VCTCXO.
Lost cost and relaxed accuracy up to 50 MHz	Mercury HJ XO series	20 to 50 MHz	25-, 50-, and 100-ppm total error, including temp. –135 dBc/Hz.	~$1.3 - $2.90	Outstanding noise for the price. Mercury reports they can offer these parts at ±5- and ±10-ppm accuracy at 25°C. That implies max temp drift over –40 to +85°C, aging, and supply can be limited to 18 ppm. Standard CMOS output.
Lost cost and relaxed accuracy up to 160 MHz	Abracon ABLNO XO series	24.576 to 160 MHz	±12 ppm typ at room temp, additional +6/–8 ppm over –30 to +85°C. –143 dBc/Hz.	~$8 - $12	Outstanding noise for the price, if accuracy is acceptable. 28-ppm max total error, 18-ppm max temp drift, 7-ppm aging => set on accuracy of 3 ppm. Nom freq error over –40 to +85°C and 10 years aging is thus 22 ppm.
High-performance VCTCXO	Taitien TKCAB	100 MHz	±1 ppm at 25°C and ±1 ppm over temp. –145 dBc/Hz	~$30 to $45	A new breakthough VCTCXO within 5 to 7 dB of the noise of low-end ovenized oscillators for about 1/3 the price.
High-performance VCTCXO	NEL AN-XOAU AN-XA7XU	60 to 128 MHz, nom 100 MHz	Grades ranging from ±0.28 to ±25 ppm, –155 to –160 dBc/Hz	Not public	High-performance VCTCXO that competes with ovenized oscillators for generally less cost and much less power.
Low-end ovenized	Taitien 2900 series	100 MHz	±0.2 ppm at 25°C and 50 ppb over temperature. –152 dBc/Hz	~$80 to $110	An excellent representative of the lower end of ovenized references, with outstanding accuracy.
Mid-grade ovenized	KVG LPN series	80 to 150 MHz, nom 100 MHz	±-0.3 ppm at 25°C 20 to 200 ppb over temp and grade. –163 dBc/Hz max	~$350 @ 100 ~$285 @ 1k	Superior noise performance for mid-grade ovenized. Options are available from "A" to "D" that trade close in noise against far out noise. Opt D pricing is shown here.
High-end ovenized	KVG ULPN series	100 MHz	±0.3 ppm at 25°C 50 to 500 ppb over temp and grade. -164 dBc/Hz max	$500 to $750 @ 1k over grade	High-grade performance at the low end of high-grade pricing. Grades P1, P2, and P3 are available.
High-end ovenized	NEL O-CIH	100 MHz	50 ppb over temp –158 to –166 dBc/Hz over grade	Not public	State of the art in the higher grades.

Listed are strong crystal oscillator candidates for low-noise synthesizers. Costs reflect moderate to medium volume for the typical applications of the part, and in some cases are estimated by the author.



2. This approximate price-versus-noise-performance graph of well-performing crystal oscillators, with trend line curve fit, gives a designer a quick view in terms of what must be spent to obtain certain phase-noise performance.

accuracy from 0.2 to 0.5 ppm and very well-controlled aging and temperature drift range cost about $70 to $1500. However, outstanding performance can be obtained by the careful designer for about $250 to $500. The price-performance ratios may be visualized by *Figure 2*.

This dB linear graph shows that the general cost versus phase-noise function is an approximate hyperbola, which is quantified and discussed in more depth in the long version at www.longwingtech.com. The main takeaway is that there's a predictable relationship here to help the designer understand a fair market price for the specifications needed. More details of examples of good performance-price ratio crystal oscillators are reviewed in *Table 2*.

Crystal-Reference Drive and Buffering

This subject is insufficiently reported on, and often more difficult than it seems at first glance. These synthesizer inputs have demanding slew-rate requirements for best noise performance, may have matching requirements, and often have some surprising voltage requirements. A voltage peak-to-peak

TABLE 3: VCOs

Part	Freq	Phase noise @ 10 kHz and 100 kHz, dBc/Hz	Tune and supply	Comments
Synergy DCRO178205-10	1785 to 2060 MHz	–109, –131	0.5 to 12 V 10 V @ 35 mA	Near the limit of available for a 2-GHz part with ±7% tune range. About 13 dB better noise than the best on-die VCO performance such as that on the LMX2495.
Synergy DCYS100200-12	1 to 2 GHz	–106, –128 (some variation over this wide band)	0.5 to 28 V 12 V @ 40 mA	Superb for a microwave octave tune range that with on-synthesizer dividers can hit any frequency from HF to 2 GHz. About 8 dB superior to a state-of-the-art on-die VCO.
Synergy DCYS200400P-5	2 to 4 GHz	–93, –116	0.5 to 18 V 5 V @ 60 mA	Excellent for an octave at this frequency, though on a normalized basis about 6 dB inferior to DCYS100200-12. About 2 dB superior to a state-of-the-art on-die VCO such as that on the LMX2495. Above 4 GHz, it's difficult to find octave VCOs that are significantly better than the best integrated.
Mini-Circuits MOS-975-119+	900 to 975 MHz	–114, –135	1 to 9 V 5 V @ 40 mA	Excellent for the ±-4% tune range, effectively –120 if divided by 2 to land mobile band. About 11 dB superior to best on-die VCOs. $15.75 @ 100.
Mini-Circuits ROS-1770-1PH19+	1710 to 1800 MHz	–111, –132	0.5 to 8 V 5 V @ 30 mA	Excellent for its ±2.6% tune range, effectively –123 divided by 4 to land mobile. About 13 dB superior to best on-die VCOs. $19.95 @ 100.
Mini-Circuits ROS-2001C-119+	2 GHz (1997 to 2003 MHz)	–126, –147	0.5 to 9.5 V 8 V @ 38 mA	Excellent for pure performance at 2 GHz, even though a point frequency product. About 29 dB better than best on-die VCOs. $39.95 @ 50.
Z-Comm ZRO0915C2LF	902 to 928 MHz	–128, –147	0 to 11 V 10 V @ 23 mA	Superb for 902- to 928-MHz low-noise apps such as RFID readers. About 23 dB better than best on-die performance. Budgetary pricing ~$19 for 1k and $13 for 10k.
Analog Devices HMC510	8.45 to 9.55 GHz	–92, –116	2 to 13 V 5 V @ 315 mA	Excellent noise in this narrowband family for frequencies in the range of 8 to 27 GHz. This particular VCO is about 11 dB better than the best on-die VCOs at 100 kHz, and others in this family in the range of 8 to 12 dB better. These have div-by-2 outputs and some also div-by-4 in order to use lower-cost, lower-frequency synthesizer ICs. $22.55 at 50.

These are noteworthy VCO candidates for low-noise synthesizers. While noise well inside the PLL bandwidth will be similar to that of integrated VCOs, these parts can provide significantly lower phase noise around and past the loop bandwidth.

swing above a minimum is needed, but usually also with a maximum that's less than the synthesizer chip supply rails. This is reviewed in some depth in the long version at www.longwingtech.com with recommended buffer parts.

There's a disconnect here in the market between optimum drive for different synthesizers and what crystal oscillators typically provide; therefore, users may have to provide their own buffering. It's a surprisingly important issue, as phase-noise degradation exceeding 10 dB can occur.

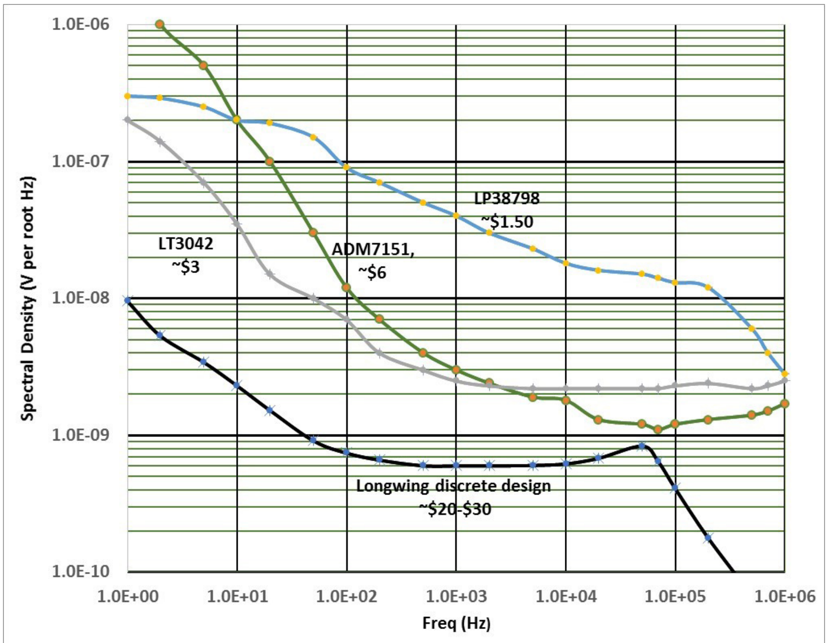
TABLE 4: REGULATORS

Regulator	Key specs	Cost and comments
TI LP38798	V_{in}: 3 to 20 V V_{out}: 1.2 to V_{in}-dropout Current limit: 800 mA Dropout: 200 mV Thermal resistance: ~35°C/W	~$1.50 at 2k distributor. Noise is first-order independent of output voltage. The low-cost choice for a low-noise, high-current, high-voltage regulator.
Linear LT3042 (200 mA) LT3045 (500 mA) LT3093 (200 mA neg) LT3094 (500 mA neg)	V_{in}: 1.8 to 20 V V_{out} : 0 to 15 V Current limit: 200 mA Dropout: 350 mV thermal Resistance: ~33°C/W	~$2.85 at 2500 distributor. Noise is first-order independent of output voltage. The ultra-low-noise choice for wide voltage range, offering positive and negative outputs.

Listed are key specifications of several top low-noise regulator choices.

Discrete VCOs

Low-noise VCOs have historically been provided as modules by companies that were specialists in pushing Leeson's Equation (Ref. 2) to the limits of physics and parts, which required high-Q resonators and a detailed understanding of all noise sources in a VCO. To remain relevant with on-die VCOs taking an ever-increasing market share, new even lower-noise VCOs have continued to come out. Such products include the narrowband VCOs offered by Mini-Circuits (www.minicircuits.com), Synergy Microwave (www.synergymwave.com), Z-Comm (www.zcomm.com), and Analog Devices.



3. Ultra-low noise regulator spectral noise density is compared in this plot. The LT3042 and ADM7151 noise curves were both obtained with 22-µF noise-filter capacitances.

The best narrowband VCOs have about 10- to 30-dB better noise performance than the best on-die VCOs. Synergy Microwave, with its metamaterial resonator VCOs, offers octave-bandwidth VCOs to about 4 GHz with phase noise that's within about 5 to 20 dB of the very best narrowband VCOs at similar frequencies, and typically about 2 to 8 dB superior than the finest on-die VCOs. Though on-die VCOs are probably taking over 80% of design-ins, high-performance discrete VCOs are still finding application in microwave links, test equipment, military communications, and wireless infrastructure. Some key examples are given in *Table 3*.

Power Supplies

Low-noise regulators represent an area of important recent advancement. Noise on supplies will directly modulate noise on a VCO, as described in Part 2 of this series. As recently as 2010, a noise floor of about 10 to 30 per root Hz was considered "ultra-low noise." These levels could induce considerable degradation of the phase noise of a low-noise VCO.

For this reason, the author had previously designed custom discrete regulators with floor of 1 nV or lower when such performance was needed. In 2015, noises as low as 2 nV were introduced to the market by Linear Technology in very convenient form. For the majority of applications, a supply noise level of 2 nV per root Hz eliminates supply noise as a practical concern.

Regulator noises for four top options are shown in *Figure 3*. In the author's opinion, the most usable low-noise regulator on the market is the 2-nV-floor LT3042 from Linear Technology (now Analog Devices). It provides voltages of 0 to 15 V at up to 200-mA output. The new LT3045 provides up to 500 mA. In addition, the recently introduced LT3093 and LT3094 deliver similar performance in negative voltage regulator form. *Table 4* shows key specifications of several top low-noise regulator choices.

Low-Noise Op Amps

Op amps are needed to boost charge-pump outputs to the higher voltages required to tune the very finest discrete VCOs. However, their noise will directly modulate noise onto the VCO output and must be very low to be transparent (Ref. 2). Op amps with noise floors approaching 1 nV have been available for many years. In recent years, though, these op amps have improved with lower input current (important for low spurs) and current noise (also very important), greater common-mode range, and higher bandwidth (important to spurs and phase shift).

However, the very lowest-noise op amps are not rail to rail, and care must be taken when locking the phase-locked loop (PLL) using these op amps. Typical methods of working with non-rail-to-rail op amps are to make use of a low-noise negative supply for the op amp, pre-charge the loop filter under software control to be within the input voltage range of the op amp, or switch in a rail-to-rail op amp during initial settling. *Table 5* lists low-noise op amps for use in low-noise synthesizers.

Summary

Delta-sigma synthesizer ICs with on-die VCOs and output dividers have reshaped the design of synthesizers in the last decade. Available at frequencies as high as 32 GHz, they can typically provide any output frequency from a few tens of MHz to their upper frequency limit. The inherent higher phase noise of on-die VCOs has been partially tamed by switching VCOs and resonators for the best open-loop on-die VCO phase noise, and then suppressing that noise with high-frequency crystal oscillators and higher phase-detector frequencies to allow for higher loop bandwidths out to approximately 200 to 400 kHz.

Discrete-VCO-based synthesizers can still offer the advantage of superior phase noise around and past the loop bandwidth. For the best narrowband and point frequency VCOs, this advantage is quite significant (about 20 to 30 dB). For octave-bandwidth VCOs that offer similar frequency flexibility to on-die VCOs, the advantage is more limited—about 2 to 8 dB for VCOs under 4 GHz.

The discrete VCO approach currently pays a penalty of

TABLE 5: OP AMPS

Op amp	Major specs	Cost and comments
TI OPA209 single and OPA2209 dual	Rail-to-rail output, 1.5-V drop on input. Voltage noise 8.1(1 Hz)-3.3-2.3-2.2-2.2 nV. Current noise 1.6 pA (1 Hz)- 0.6-0.5-0.5. Supply 4.5 to 36 V. Input bias 1 to 8 nA. 18-MHz GBW.	Single $1.10 @ 1k Dual $1.65 @ 1k Lower input bias and noise current than most ultra-low-noise op amps can sometimes enable, outperforming op amps with lower voltage noise.
TI OPA1611 single and OPA1612 dual	Output rail to rail, input from V_{SS} + 2 to V_{CC} – 2 V. 1-Hz to 10-kHz voltage noise of 7-3-1.5-1.2-1.1 nV/√Hz. Current noise 11 pA (1 Hz)- 4.5-2.9-2.7-2.7. Supply 4.5 to 36 V. Input bias 60 to 350 nA. 40- to 80-MHz GBW.	Single $1.75 @ 1k Dual $2.75 @ 1k Outstanding noise performance, current noise is about 5X the OPA209, but much lower than competing MAX9632. The OPA211 is a more expensive version with better input voltage limits.
TI LMP7731 (single) and LMP7732 (dual)	Rail-to-rail input and output. Voltage noise 4.2 (1 Hz)-3.1-3.0-2.9 nV. Current noise 8 pA (1 Hz)-3-1.2-1.1 pA. Supply 1.8 to 5.5 V, input bias 1.5 to 5 0nA. 22-MHz GBW.	Single $0.63 @ 1k Dual $1.05 @ 1k Lowest noise RRIO part from TI. The competing Linear LT1678 dual RRIO has noise of 7.5 (1 Hz)-4.5-4.0-3.9 nV.
Linear LT1677	Among lowest-noise RRIO op amps with higher voltage. Voltage noise 18 (1 Hz)-5.2-3.3-3.2 nV. Current noise 1.2 pA (10 Hz)-0.4-0.3. 3- to ±18-V supply, ~3 mA 7.2-MHz GBW.	~$2.80 @ 1000 distributor. LT1678 is a similar dual version, ~$3.15 @ 1000 distributor. Suitable for low-noise (not ultra-low noise) single op-amp loop filters where its rail-to-rail performance simplifies circuit design of locking problems that unassisted non-RR op amps may suffer.
TI OPA2156	Dual low-cost, low-noise, high-voltage RR op amp. Voltage noise 150 (1 Hz)-40-11-4-2.9 nV. Current noise 19 fA at 1 kHz. 4.5- to 36-V supply, ~4.4 mA. 25-MHz GBW.	First of a new family, single op-amp versions likely to follow. Dual: $1.25 @ 1k. High 1/f corner ~700 Hz, but this can be suppressed by a wideband synthesizer. Suitable for single op-amp loop filter with op amp to spare.
TI LM7321 LM7322	RR input and output. Noise 100 (1 Hz)-40-18-15 nV. 2.5- to 32-V supply, 1.3 mA. 20-MHz GBW.	Single: $0.71 @ 1k Dual: $0.97 @ 1k Suitable as a rail-to-rail op amp for settling the active filter prior to switching in an ultra-low-noise non-RR op amp.

Listed are low-noise op amps for use in low-noise synthesizers. The shorthand W-X-Y-Z here refers to spectral noise density (voltage or current) at frequencies spaced a decade apart, usually starting at 1 Hz.

moderately higher noise (approximately 3 to 4 dB) over part of the range within the loop bandwidth due to the best PLL noise (charge pump and divider noise) being available only for VCO on-die synthesizers and not for synthesizers supporting external VCOs. The discrete VCO approach also requires extra parts for higher voltage supplies and active loop filters. Still, in markets like test equipment, microwave links, wireless infrastructure, and low-noise communications, there are places for the discrete VCO approach. Examples will be shown in the concluding fifth article of this series.

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