From May 2008 *High Frequency Electronics*

Building a Microwave Frequency Synthesizer — Part 1: Getting Started

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Synthesizer design methods have evolved over time, and this series of articles offers an update on well-established and recently-developed techniques

The frequency synthesizer is a key building block of virtually any microwave test and measurement, communication or monitoring system [1-5]. Synthesizers come in a variety of forms ranging from a tiny PLL chip to a bench-top signal generator. Traditionally we imagine them as a connectorized metal box or "brick" which can be put into a more complex instrument or subsystem.

This series of articles presents an overview of microwave frequency synthesizer technologies and design techniques with a specific focus on the synthesizer "brick" modules. It starts with general requirements and specifications followed by a review of the main synthesizer architectures. Direct analog, direct digital, and indirect techniques are compared in terms of performance, circuit complexity, and cost impact. A simple, single-loop PLL example is used to demonstrate the most important aspects of the design process from a general block diagram and component selection to schematic, board layout, assembling, and testing. The design trade-offs are further analyzed and complemented with a detailed review of the most advanced synthesizer solutions including DDS-based and multiloop schemes.

Reviewing the Specifications

A frequency synthesizer can be treated as a black box that translates one (or more) input base (reference) frequency to a number of output frequencies as shown in Figure 1. The box contains individual components such as voltage-controlled oscillators, frequency dividers, multipliers, phase detectors, mixers, amplifiers, etc., which being properly connected, perform this translation function. Although all synthesizers exhibit significant differences as a result of specific applications, they share basic characteristics and design objectives as listed below. The synthesizer's characteristics are divided into a few groups depicting its frequency and timing (i.e., frequency coverage, resolution, stability, switching speed); spectral purity (i.e., harmonics, spurious, phase noise); output power (i.e., output power, flatness, control range). In addition to these signal-related behaviors, a specification defines how it interfaces to the outside world (control interface, bias, power consumption, size, etc.).

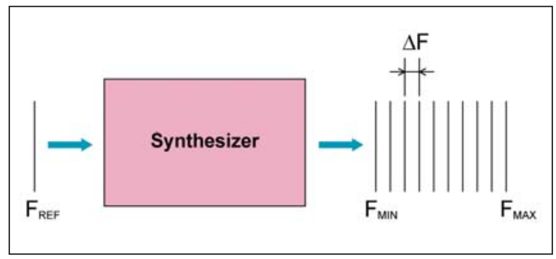

Figure 1 · The fundamental concept of a frequency synthesizer.

Frequency Coverage or *Range* and *Frequency Resolution* or *Step Size* are the fundamental synthesizer specifications set by a particular application. Some applications (e.g., test and measurement) require wide bandwidth and fine frequency resolution while others need a relatively narrowband (10-20%) coverage with a rough step or just a single fixed frequency.

Frequency Stability is determined by the

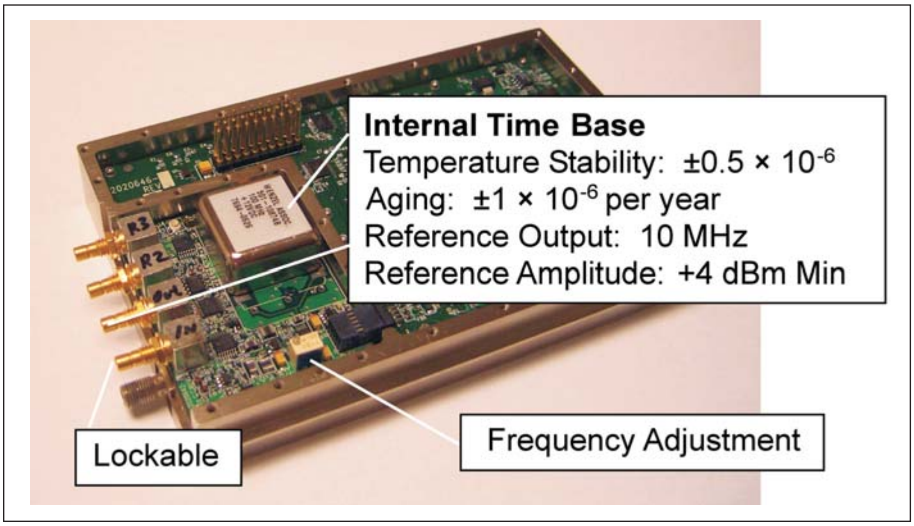

Figure 2 · Synthesizer time base and synchronization.

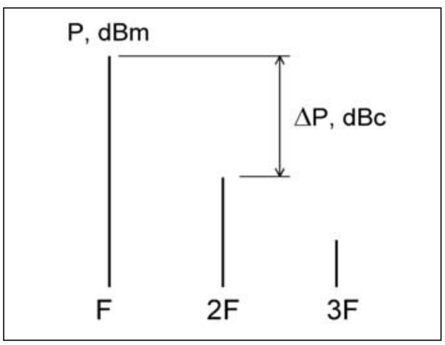

Figure 3 · Harmonics.

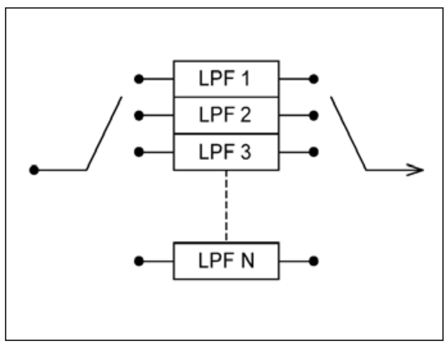

Figure 4 · Switched filter bank.

reference signal, which can be internal or external to the synthesizer. The synthesizer usually includes a temperature-compensated (TCXO) or ovenized (OCXO) crystal oscillator that serves as both an internal time base and low phase noise source (Figure 2). The internal time base (usually 10 MHz) can be locked to an external reference signal or used by itself for synchronization of external equipment. It is also good practice to use mechanical or electronic frequency adjustment means to compensate for internal time base aging.

Switching or *Tuning Speed* determines how fast the synthesizer jumps from one desired frequency to another and is normally specified as time spent by the synthesizer between jumps. The switching speed is determined by a particular synthesizer scheme and is usually a trade-off among other synthesizer parameters, such as step size, spurious, or phase noise.

Harmonics appear in the synthesizer spectrum as multiples of the output frequency due to signal distortion in non-linear components such as an amplifier (Figure 3). Harmonics usually do not cause serious trouble since they are very well separated from the main signal. The levels of –20 to –30 dBc are acceptable in many cases, although they should be reduced to –50 or –60 dBc in some harmonic-sensitive applications or test and measurement instruments. For a narrowband synthesizer, it is easily achieved by putting a low-pass filter at the output; a switched filter bank (Figure 4) is required for synthesizer bandwidths reaching or exceeding an octave.

Sub-Harmonics are created at frequencies that are "sub-harmonically" related to the main signal as shown in Figure 5. A typical example is a frequency doubler, which is often used to extend the output frequency range. As a non-linear device, the doubler generates a number of harmonics of the incoming signal. Moreover, it usually employs a balanced configuration that tends to suppress the odd harmonics and, therefore, accent the desired second harmonic. Since the second harmonic becomes our main signal, all the odd products do not meet the harmonic relationship in respect to the desired output anymore and are specified as sub-harmonics. Another example is divider leakage, which can be found in PLL circuits as shown in Figure 6.

Spurious Signals or *Spurs* are undesired artifacts created by synthesizer components at discrete frequencies that are not harmonically related to the output (Figure 7). Spurious can come from different sources such as PLL reference spurs, DDS spurs, mixer sidebands and LO leakages, some internal auxiliary signals or even external signals coming through bias and control interface circuits. Although the spurs look randomly positioned in the synthesizer spectrum, their location is determined by a particular synthesizer architecture and frequency plan. In contrast to harmonics, the spurs are much more troublemaking products that can limit the ability of receiving systems to resolve and process a desired signal. They can be located very close to the main tone and, therefore, cannot be filtered. Thus, the spurious level has to be minimized, typically to –60 dBc relative to the main signal, although many applications require bringing this level down to –70, –80 dBc and even below.

Phase Noise is another measure of the synthesizer frequency instability,

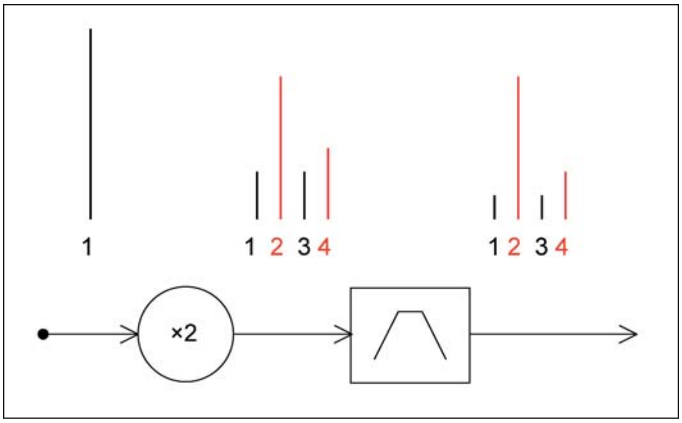

Figure 5 · Sub-harmonic generation scheme.

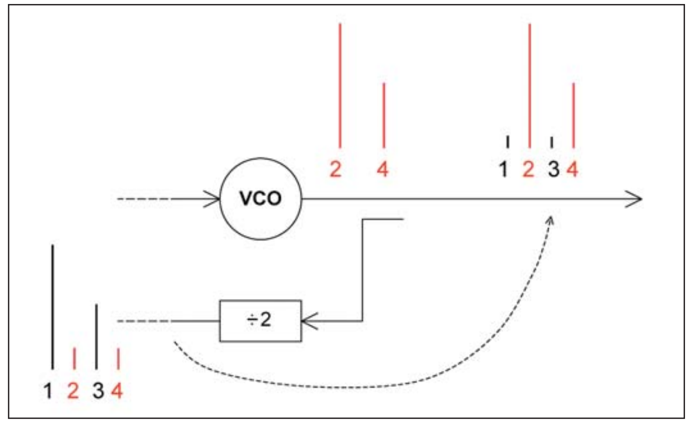

Figure 6 · Another sub-harmonic example.

which manifests itself as random frequency fluctuations around the desired tone (Figure 7). It is one of the major parameters that ultimately limits the sensitivity of receiving systems. Synthesizer close-in phase noise strictly depends on the reference signal as well as the particular architecture used to derive its output from the reference. Indirect synthesizers also rely on tunable oscillator noise, which can supersede the multiplied reference noise at high frequency offsets. Phase noise minimization is a primary design concern; it requires a specific effort and is usually a trade-off between other synthesizer parameters.

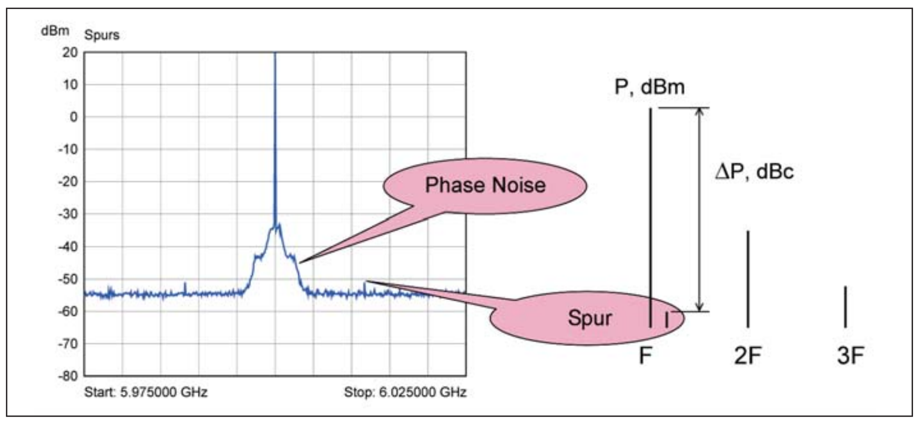

Figure 7 · Spurious and phase noise in the output spectrum.

Output Power can range in wide limits depending on a particular application. A typical scenario assumes the frequency synthesizer as an LO source driving a frequency mixer in a variety of up- and down-conversion schemes. This normally requires +10 to +17 dBm output signal, although some applications need more power. The output power can be controlled with an attenuator as shown in Figure 8. The same control can be used to reduce output power variations versus frequency (specified as output power flatness) by applying a proper correction voltage setting, stored in synthesizer memory. A more precise control can be achieved with a closed-loop automatic level control scheme (ALC) by adding a directional coupler and detector, which generates a correction signal that is fed back to the attenuator (Figure 9). This configuration does not depend on the amplifier gain and power variations; it is also less sensitive to the output load mismatch due to the coupler directivity.

The *Control Interface* should be fast, versatile, and easy to use. Although, there is no set industry standard for “brick” level products, serial peripheral interface (SPI) is the most prevalent, offering full duplex communication, relatively high throughput and flexibility. RS-232 is a simple and useful interface used when the distance from the

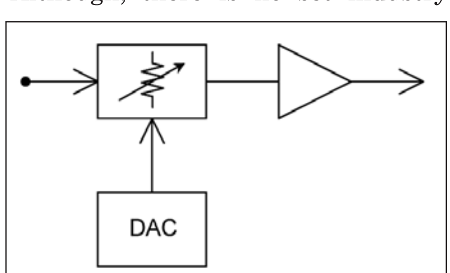

Figure 8 · Output power control using an attenuator.

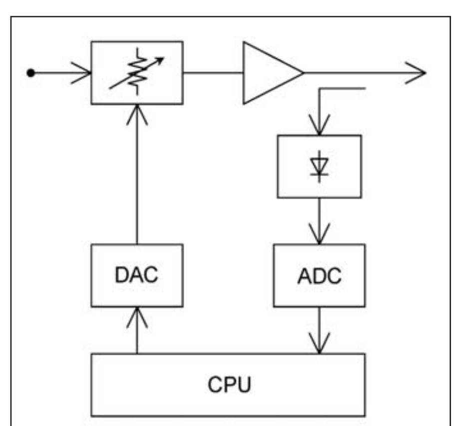

Figure 9 · Closed-loop digital ALC.

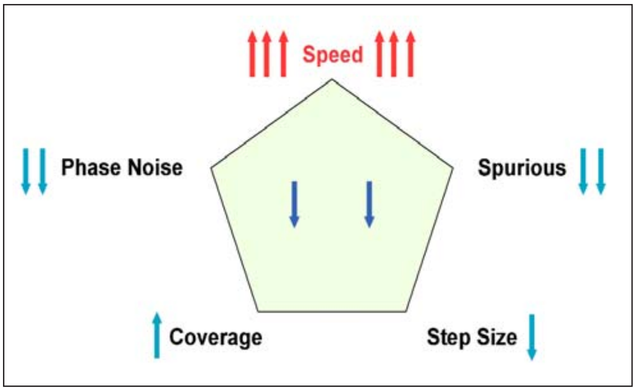

Figure 10 · Synthesizer design trade-offs.

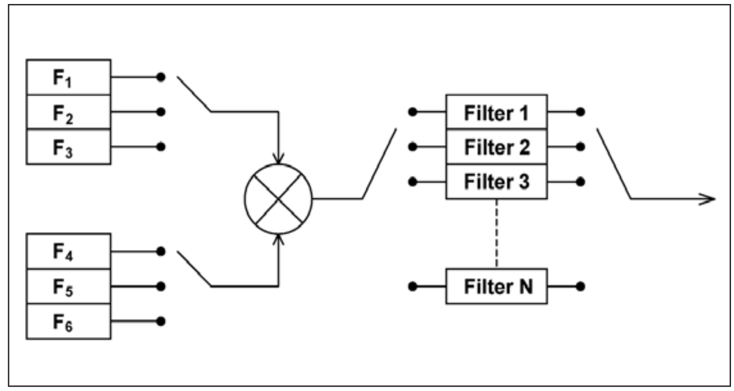

Figure 11 · Direct analog synthesizer concept.

master controller exceeds SPI capability. Another very desirable interface is universal serial bus (USB), which allows instant deployment or just evaluation of the synthesizer from a laptop computer. All the mentioned interfaces require a CPU or microcontroller internal to the synthesizer to perform data communication or translation functions. The designer should be very careful selecting a processor to keep the processing time at a minimum. Ideally, the synthesizer should have a direct access option; in other words, the ability to communicate directly with the components within the synthesizer. Another way to eliminate the processing time is utilizing a "list mode" that defines a list of frequencies to jump between. Knowing these frequencies, one can pre-calculate and memorize all necessary parameters required to control individual components of the synthesizer.

Other specifications cover bias, power consumption, mechanical and environmental characteristics as well as some special features such as a dual output, various modulation options, etc.

Design Challenges

The microwave industry feels persistent pressure to deliver higher performance, higher functionality, smaller size, lower power consumption, and lower cost synthesizer designs. What parameters are the most important? Although the answer strictly depends on a particular application, frequency coverage, resolution, spectral purity, and switching speed require most of the designer's effort as illustrated in Figure 10. The ideal synthesizer should be preferably broadband with a fine frequency resolution that allows addressing a bigger number of potential applications. On other hand, the phase noise and spurious are even more important parameters since they determine the ultimate performance of a microwave system driven by the synthesizer. However, the major technology challenge is in increasing the synthesizer tuning speed as dictated by the ongoing increase of the data rates of modern microwave systems. The time spent by the synthesizer jumping between the frequencies becomes more and more valuable since it cannot be used for data processing. While many microwave systems still work adequately with millisecond switching speed, new equipment demands microsecond operation together with similar performance (phase noise, spurious) of the low speed designs [2, 3]. Obviously, this presents serious design difficulties and trade-offs. Another challenge is cost reduction. Although it is considered to be a "standard" requirement, it drastically narrows the designer's choices. These particular requirements—fast switching speed, excellent spectral purity, and low cost—are the key drivers in the development of new frequency synthesizers.

The synthesizer characteristics heavily depend on a particular technology. While reviewing traditional frequency synthesizer architectures, we specifically address the current technology trend toward increasing the synthesizer tuning speed, improving the spectrum purity as well as reducing its complexity and cost. The main architectures along with their characteristics and trade-offs are described below.

Direct Analog Synthesizers

The direct analog synthesizer is today's most advanced technique offering unprecedented speed and phase noise performance [6, 7]. The desired signal is obtained by mixing base frequencies followed by switched filters as depicted in Figure 11. The base frequencies can be extracted from low-frequency (crystal, SAW) or high-frequency (CRO, DRO, metal cavity, sapphire, etc.) oscillators by frequency multiplication, division, or phase locking.

The key advantage of the direct analog technique is extremely fast switching speed, ranging from micro- to nanoseconds. Another distinct advantage is the ability to generate very low phase noise output due to the usage of the components (e.g., mixers) with negligibly low residual noise in comparison with the base frequency sources. Thus, the direct

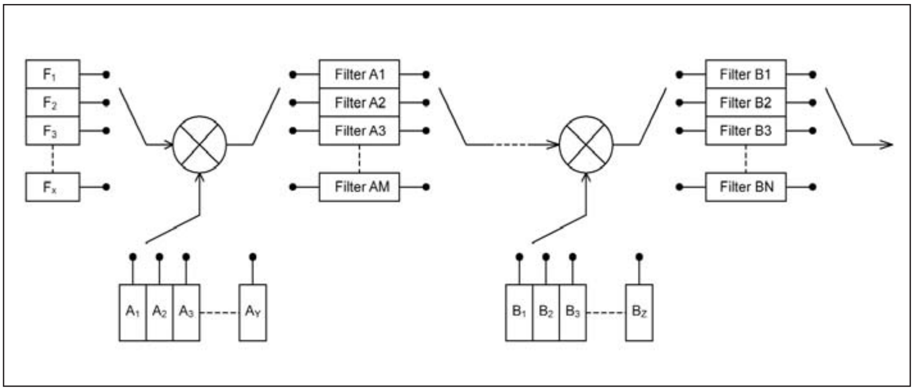

Figure 12 · Direct analog synthsizer with extended coverage.

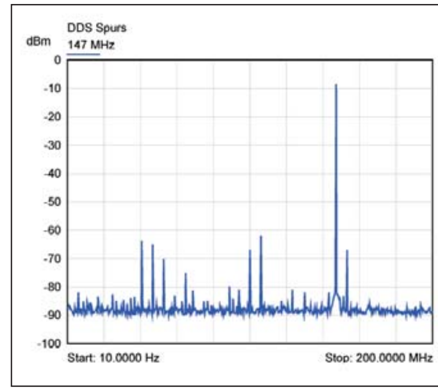

Figure 14 · DDS output spectrum.

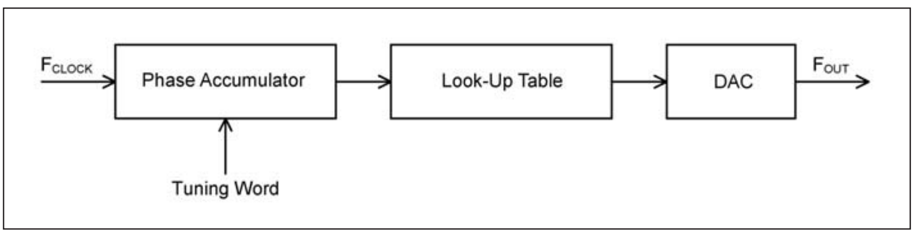

Figure 13 · Direct digital synthsizer (DDS).

analog synthesizer phase noise mainly depends on the noise of the available reference sources and can be potentially very low.

The main disadvantage of the indicated topology is limited frequency coverage and step size. In our example (Figure 11) only eighteen output frequencies can be generated even by utilizing both mixer sidebands. The number of output frequencies can be increased by using a higher number of base frequencies and/or mixer stages as shown in Figure 12. However, this rapidly increases the design complexity and overall component count.

Another serious problem is a large amount of undesired mixing products that have to be carefully planned and filtered out. Special attention should be paid to switched filter isolation and leakages too. Although a large variety of mixing and filtering organization schemes is possible, they tend to be hardware intensive if a small frequency step and wide coverage are required. Therefore, while this approach offers excellent tuning speed and phase noise characteristics, its usage is limited to applications where fairly high cost can be tolerated.

Direct Digital Synthesizers

In contrast to traditional analog concepts, direct digital synthesizers (DDS) utilize digital processing to construct an output signal waveform from a base (clock) frequency [8, 9]. Initially, a digital representation of a desired signal is created (Figure 13), then it is reconstructed with a digital-to-analog converter (DAC) to a sinusoidal or any other desired shape. This process is extremely fast (mainly limited by the digital control) that results in very high switching speeds, comparable with direct analog schemes. DDS also provides reasonably low phase noise even showing an improvement (limited by its residual noise floor) over the phase noise of the clock source itself. However, the most valuable DDS feature is its exceptionally fine frequency resolution, which is determined by the length of the DDS phase accumulator. Sub-Hz levels are easily achieved.

The main disadvantages are limited usable bandwidth and inadequate spurious performance. While DDS starts working from nearly DC, its highest frequency is limited by the Nyquist criteria to within one half of the clock frequency. Moreover, a practical design requires an output lowpass filter for reconstructing the signal waveform, which further decreases the highest operation frequency to about 40% of the clock signal. Another serious problem is a high spurious content (Figure 14) due to quantization and DAC conversion errors, which generally prohibits direct multiplication of the DDS output.

Due to the mentioned bandwidth and spurious limitations, the DDS technique alone is rarely utilized at microwave frequencies. Rather DDS is used as a fine frequency resolution block in direct analog and indirect architectures.

Indirect Synthesizers

Indirect frequency synthesizers utilize phase-lock loop (PLL) techniques offering smaller step size and lower complexity in comparison with direct analog schemes [10-22]. A typical single-loop PLL synthesizer includes a tunable voltage-controlled oscillator (VCO) generating a signal that is fed back to a phase detector through a frequency divider with a variable frequency division ratio N as

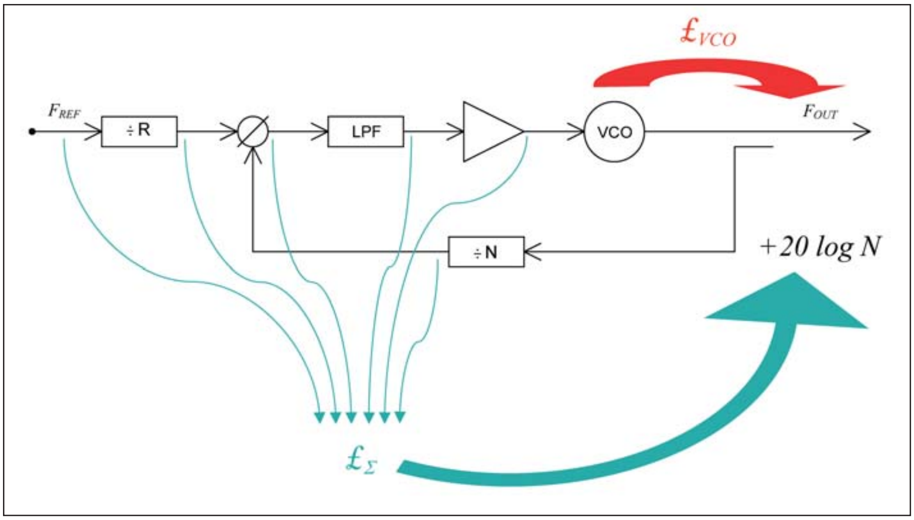

Figure 15 · PLL block diagram and noise sources.

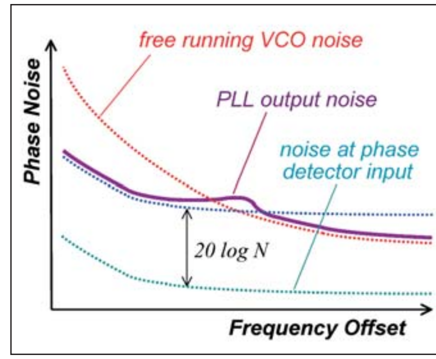

Figure 16 · PLL phase noise.

shown in Figure 15. The other input of the phase detector is a reference signal equal to a desirable step size. Also, the reference frequency can be divided down by another divider to reduce the step size. The phase detector compares the signals at both inputs and generates an error voltage, which following filtering and amplification, slews the frequency of the VCO to the lock frequency given by $F_{OUT} = F_{PD} \times N$, where F_{PD} is the comparison frequency at the phase detector input.

The major advantages of this scheme are reduced levels of spurious signals owing to the low-pass filter action of the loop and much lower level of complexity compared to the direct analog synthesizers. The main disadvantages are longer frequency switching time (which is inversely proportional to the loop bandwidth and consequently step size) and considerably higher phase noise in comparison with direct analog techniques.

The synthesizer noise outside the PLL filter bandwidth is mainly determined by the VCO free-running noise as shown in Fig. 16. The phase noise within the loop filter bandwidth is given by $\pounds = \pounds_{PD} + 20 \log N$, where $\pounds_{PD}$ is the cumulative phase noise of the reference signal, phase detector, reference and feedback divider, loop filter and amplifier referred to the phase detector input (Fig. 15). Thus, the close-in phase noise depends on the reference as well residual noise of individual synthesizer components and is further degraded by large division ratios required to provide a high-frequency output with a fine resolution.

The single-loop synthesizer's characteristics can be improved with a number of techniques such as fractional-N as well as employing a frequency conversion (mixing) within the synthesizer feedback path. Although these solutions complicate the synthesizer schematic, the complexity can be balanced to a high-performance and reasonably priced design.

Next Month

This article will be continued in the next issue, reviewing individual components used in the synthesizer design.

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