CURRENT STATE AND DEVELOPMENT TRENDS OF MICROWAVE FREQUENCY SYNTHESIZERS

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Abstract – This article discusses the current state and development trends of microwave frequency synthesizers for test-and-measurement instruments. The discussed trends are also applicable for other synthesizer types used as modules in more complex systems. Test-and-measurement synthesizer market is estimated at $300M with an annual growth rate about 3%.

A modern trend for the development of frequency synthesizers is associated with low phase noise, low spurious and fast switching speed. Important parameters also include operating frequency range, frequency resolution, modulation capabilities as well as size and cost characteristics. The main architectures based on direct analog, direct digital and indirect synthesis are evaluated. As of today, traditional indirect phase-lock-loop (PLL) architectures still dominate. On the other hand, direct analog synthesis is the most advanced approach that demonstrates extremely fast switching speed and low phase noise. Nevertheless, future developments are associated with direct digital synthesis (DDS) due to the rapid progress in solid-state technologies. DDS are currently available as special integrated circuits (IC) or can be build using field-programmable logic arrays (FPGA) and high-frequency digital-to-analog converters (DAC). Parallel (multichannel) digital structures coupled with high-frequency DACs allow generating output signals at microwave frequencies. Further improvements are possible using two or more DACs in an interleaved data mode. Wider frequency coverage through several tens of gigahertz and lower spur characteristics are expected.

The article notes that modern frequency synthesizers allow generating complex signals using vector IQ-modulation. The modulation bandwidth is constantly increases through hundreds of megahertz or even several gigahertz. Further advances in microwave frequency synthesizers are associated with new reference types such as sapphire-loaded cavity oscillators with combined frequency stabilization as well as optoelectronic methods.

Key words: frequency synthesizer, signal generator, test-and-measurement instruments, phase noise, switching speed

I. INTRODUCTION

Frequency synthesizers are important components of many systems from commercial communication systems through test-and-measurement instruments [1]. In essence, they appear virtually in all electronic equipment such as:

- test-and-measurement instruments;
- receivers and transmitters;
- various communication systems (including new projects such as WLAN, 5G, etc.);
- radars;
- medical equipment.

Mobile communication is today's most spread out systems where frequency synthesizers are utilized. Since size and cost characteristics are extremely important there, frequency synthesizers are usually realized using indirect PLL integrated circuits [2-5]. Many books and articles reveal this subject in detail [6-11]. Nevertheless, synthesizer designers feel persistent pressure to deliver new solutions with higher performance characteristics.

This article discusses the current state as well as development trends of microwave frequency synthesizers mainly for test-and-measurement applications. However, the discussed trends can be applied to other applications (such as synthesizer modules for complex microwave systems) as well. According to some research [12], the total market for test-and-measurement microwave synthesizers is estimated at $300M with an annual growth rate about 3% (Fig. 1). Another more recent research [13] reveals synthesizer market potential by geographical regions as shown in Table 1 (also including arbitrary waveform generators - AWG instruments).

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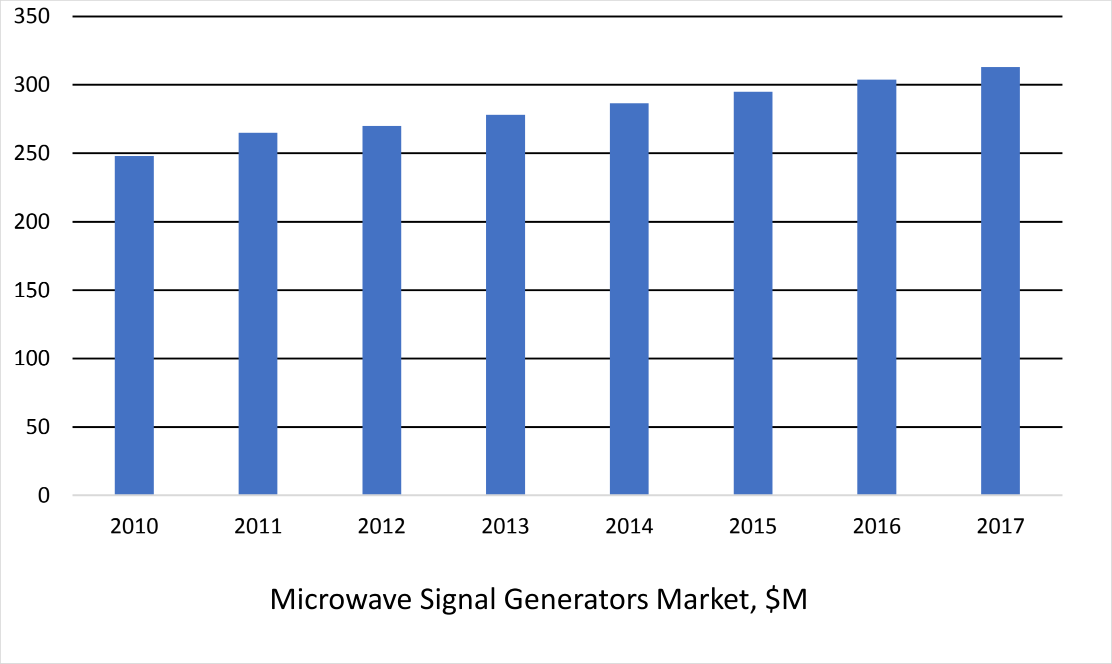

Fig. 1 Microwave signal generators market potential

Signal generators by geographical regions, $M							
Region / Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
North America	110.84	116.82	123.63	131.38	140.57	151.76	165.38
Europe	103.00	107.16	111.91	117.25	123.66	131.45	140.84
Asia-Pacific	88.03	98.26	109.98	123.49	139.33	158.43	181.65
Others	40.54	43.86	47.7	52.09	57.33	63.55	71.23
Total	**342.41**	**366.10**	**393.22**	**424.21**	**460.89**	**505.19**	**559.11**

Table 1 Signal generators market by geographical regions (including AWG)

A modern trend for the development of frequency synthesizers is associated with low phase noise, low spurious and fast switching speed. Important parameters also include operating frequency range, frequency resolution, modulation capabilities as well as size and cost characteristics [14].

Obviously, modern test-and-measurement synthesizers should provide wide frequency coverage with fine frequency resolution, low phase noise and low spurs. However, a key new requirement and essentially a modern trend is providing fast switching speed. The time spent by the synthesizer transitioning between frequencies becomes increasingly valuable since it cannot be used for data processing. Even traditional test-and-measurement instruments demand faster switching speed together with comparable spectral purity of the low speed designs. Another important driver is associated with complex modulation capabilities (such as IQ-modulation). In spite of technical challenges, small size and low cost are also desirable characteristics and another challenge in the development of modern frequency synthesizers. All these requirements put certain challenges and restrictions in selection of a particular synthesizer architecture.

II. ARCHITECTURAL SOLUTIONS

Traditionally synthesizer are classified into two main groups (Fig. 2) based on direct and indirect architectures. Furthermore, both direct and indirect synthesizers can be accomplished with analog and digital techniques. However, a practical synthesizer is usually a hybrid design that combines both analog and digital techniques to achieve specific design goals [2-7].

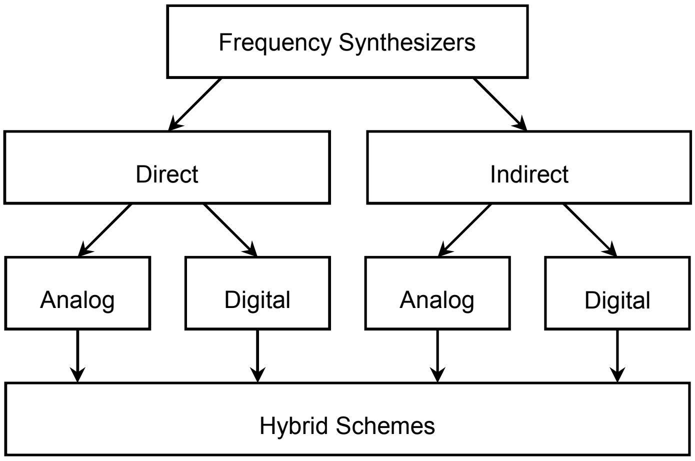

Fig 2 Frequency synthesizer classes

A. Direct Analog Synthesis

Direct analog synthesizers are realized by mixing base signals at some fixed frequencies followed by switched filters as shown in Fig. 3. The base signals can be obtained from low-frequency (e.g., crystal, SAW) or high-frequency (e.g., DRO, metal cavity, etc.) oscillators by frequency multiplication, division or phase-locking.

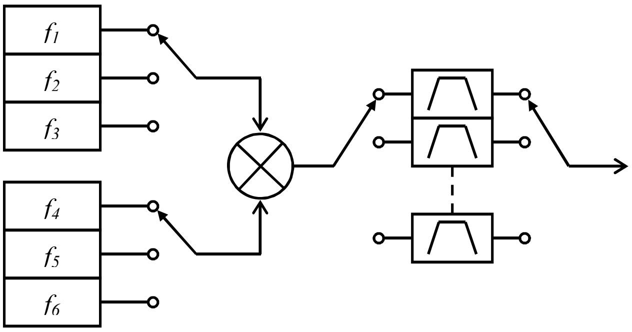

Fig. 3 Direct analog synthesizer concept

The main advantage of the direct analog synthesizers is extremely fast switching speed, ranging from micro- to nanoseconds. Another distinct advantage is the ability to generate low phase noise due to usage of components with negligibly low residual noise compared to the base frequency sources. Hence, the direct analog synthesizer phase noise mainly depends on the noise of the available fixed-frequency sources and can potentially be very low. The main disadvantage of the indicated topology is limited frequency coverage and step size. The number of output frequencies can be increased by using a larger number of base frequencies and/or mixer stages. However, this increases the design complexity and overall component count. Another serious problem is a large number of undesired spurious products generated by mixer stages. These spurs have to be filtered thoroughly that is a serious challenge for the development of a particular synthesizer frequency plan.

Another promising approach is based on the concept of consecutive spreading of the synthesizer operating frequency bandwidth [15]. Such a synthesizer structure consists of several cascades that include a programmable frequency divider, mixer and bandpass filter (or switched filter bank) as shown in Fig. 4. Several LO frequencies generated by the programmable divider are utilized. The input frequency bandwidth and division coefficients are selected in such a manner that $\Delta f_{i+1} > \Delta f_i$ at continuous coverage. Therefore, every mixer stage increases operating bandwidth until it reaches a desired value.

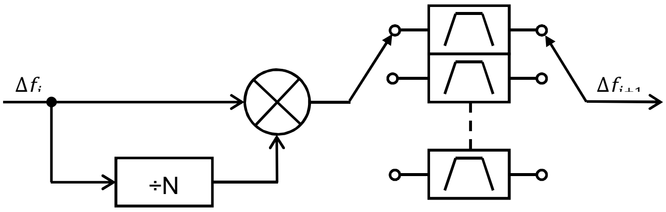

Fig 4 Frequency bandwidth spreading

In general, although a large variety of mixing and filtering organization schemes is possible, however, they tend to be hardware intensive if a small frequency step size and wide coverage are required. Therefore, while direct analog synthesizers offer extremely fast switching speed and low phase noise, its usage is limited because of high cost characteristics.

B. Direct digital synthesis

In contrast to traditional analog solutions, direct digital synthesizers (DDS) utilize digital signal processing to construct an output signal waveform from an input clock signal [16]. DDS switching speed is mainly limited by its control interface and can be extremely fast - comparable with direct analog schemes. DDS also provides reasonably low phase noise. However, the most valuable DDS feature is its exceptionally fine frequency resolution; sub-Hz levels are easily achieved. The main disadvantages are limited usable bandwidth and high spurs mainly due to quantization and digital-to-analog conversion errors.

DDS are currently available as special integrated circuits or can be build using field-programmable logic arrays (FPGA) and external DAC. Parallel (multichannel) digital structures coupled with high-frequency DACs allow generating output signals directly at microwave frequencies. Further improvements (wider frequency coverage, lower spurs) are possible using two or more DACs in an interleaved data mode as shown in Fig. 5.

Overall, DDS have a tremendous potential for future growth. The extension of DDS usable bandwidth together with its spurious content reduction is the key improvement required by industry. DDS is also widely used in direct analog and indirect synthesizers to provide a desired frequency resolution.

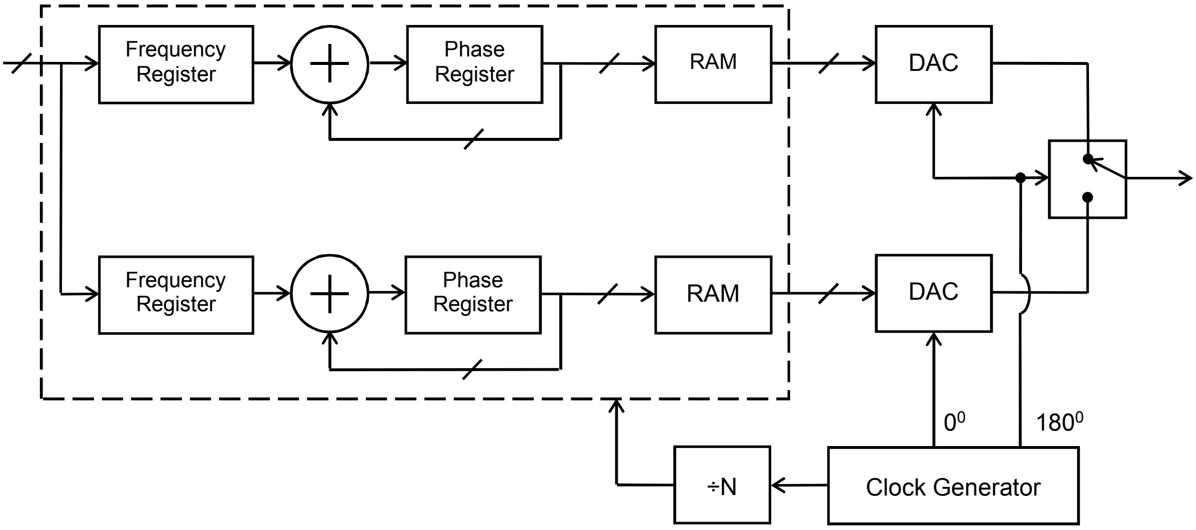

Fig. 5 Multichannel DDS with interleaved DACs

C. Indirect Synthesis

Indirect PLL synthesizers use an additional high-frequency oscillator to generate an output signal at microwave frequencies that is in a certain relationship with the reference signal. The major advantages of PLL synthesizers are reduced levels of spurious signals owing to the low-pass filter action of the loop, and much lower level of complexity compared with the direct analog synthesizers. The main disadvantages are longer frequency switching time (due to a natural delay involved in the phase-lock-loop approach) as well as considerably higher phase noise in comparison with direct analog schemes. Phase noise heavily depends on the overall division coefficient within phase-lock loop that can be relatively large in order to provide a high-frequency output with a fine resolution. There is a number of solutions to decrease the loop division coefficient, for example, using fractional division ratios.

On the other hand, there are solutions that allow eliminating a frequency divider from the PLL and, therefore, drastically decreasing phase noise. These solutions include various offset schemes as well as multiloop architectures. It is also possible to use some direct analog synthesis methods, for example, using a chain of mixers within phase-lock loop (Fig. 6). All mixer LO signals can be extracted from a common reference source. In this case, all harmonic and intermodulation products generated by the mixer chain are multiples of the phase detector frequency and can be easily filtered out [17]. Further improvements are possible by inserting a frequency multiplier into the feedback path as conceptually shown in Fig. 7.

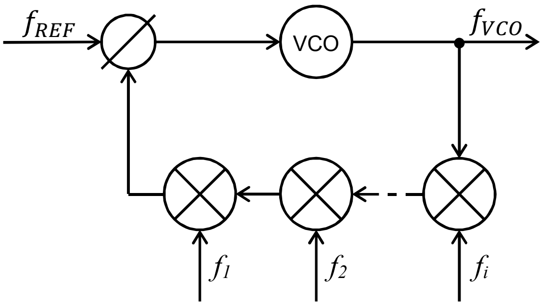

Fig. 6 Consecutive frequency conversion within phase-lock loop

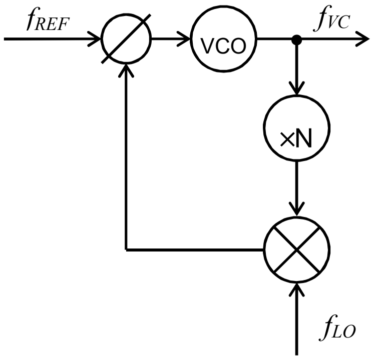

Fig. 7 Frequency multiplication within phase-lock loop

III. GENERATION OF REFERENCE FREQUENCY

Phase noise of modern microwave synthesizers mainly depends on utilized references such 100 MHz oven-control crystal oscillators (OCXO). The 100 MHz OCXO can be locked to a 10-MHz OCXO to reduce phase noise at low frequency offsets. Similarly, a higher-frequency oscillator (such as SAW of DRO) can be added to improve phase noise at high frequency offsets. A combined reference source (that contains several oscillators locked to each other) can be used to achieve the lowest phase noise profile at any frequency offset as shown in Fig. 8. Further improvements are possible using higher-Q resonators such as a sapphire-loaded cavity oscillator with combined frequency stabilization [18, 19] or optoelectronic methods [20]. For example, the phase noise around -170 dBc/Hz at 10 kHz offset at 10 GHz output for a sapphire-resonator-based oscillator with combined frequency stabilization has been reported [21].

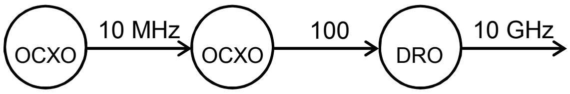

Fig. 8 Combined reference source

IV. MODULATION

Frequency synthesizers for test-and-measurement instruments traditionally provide various analog modulation formats such as amplitude, frequency, phase and pulse modulation. However, these days the industry demands more complex vector modulation formats such as IQ modulation [22]. Modulation bandwidth tends to grow constantly from hundreds of megahertz to several gigahertz. Designing vector modulators with wide modulation bandwidth and stable characteristics in a wide temperature range is not a trivial task.

IV. CONCLUSIONS

The test-and-measurement synthesizer market is currently estimated at $300M with an annual growth rate about 3%. Modern synthesizers exhibit wide frequency coverage with fine frequency resolution, low phase noise and low spurs. However, a key requirement and essentially a modern trend is providing fast switching speed.

As of today, traditional indirect PLL architectures still dominate. On the other hand, direct analog synthesis is the most advanced approach that demonstrates extremely fast switching speed and low phase noise. Although direct analog synthesizers are usually quite expensive, nevertheless, they can be successfully used at some applications where fairly high cost can be tolerated.

Future developments are associated with direct digital synthesis due to the rapid progress in solid-state technologies. The extension of DDS usable bandwidth to several tens of gigahertz with its spurious content reduction is expected. Modern synthesizers are also expected to generate complex waveforms using vector IQ-modulation. Further major breakthroughs are expected operating the reference with other physical principles or materials such as sapphire-loaded cavity oscillators with combined frequency stabilization as well as optoelectronic methods.

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