LECTURE 010 – INTRODUCTION TO FREQUENCY SYNTHESIZERS

(References: [1,5,9,10])

What is a Frequency Synthesizer?

A frequency synthesizer is the means by which many discrete frequencies are generated from one or more fixed reference frequencies.

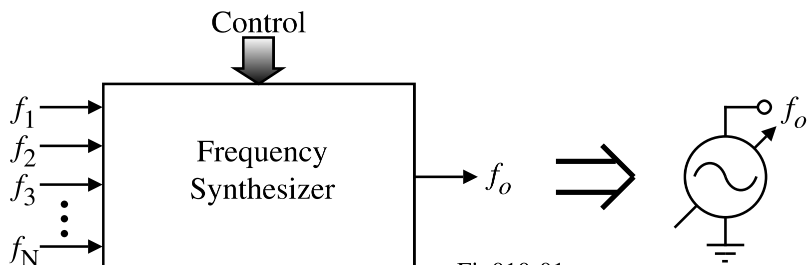


Fig010-01

- The reference frequencies are stable and spectrally pure frequency typically generated from a piezoelectric crystal.
- Modern frequency synthesizers must provide many discrete output frequency so that it is impractical to generate the frequencies by having a reference frequency for each desired output frequency.
- The control input determines the value of the frequency synthesizer output frequency, f_o

Characterization of a Frequency Synthesizer

- Output frequency range - $f_{min} \leq f_o \leq f_{max}$
- Frequency accuracy - $f_o \pm \Delta f$ (typically in % or parts per million, ppm)
- Frequency switching time –

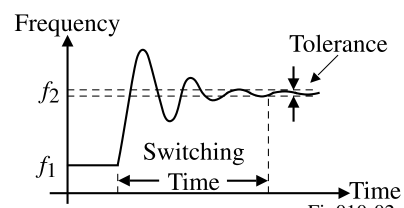


Fig010-02

- Frequency resolution (channel spacing)
- Spectral purity (noise) –

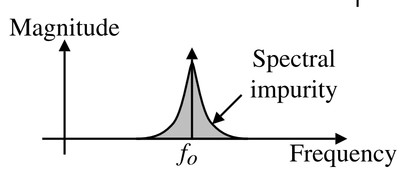


Fig010-03

- Frequency stability as a function of time, temperature and power supply
  - Expressed as parts per million per influence (time, temperature or power supply)
  - Short term (drift)
  - Long term (aging)
- Spurious outputs –

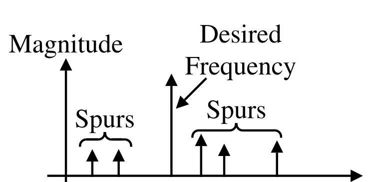


Fig010-04

Reference Frequencies

Ideally, the reference frequency should be a single frequency independent of all possible influences. It is very difficult to achieve an output frequency with better characteristics than the reference frequency.

Resonators

The reference frequency can be generated using resonators. Resonator technologies include:

- Quarter-wave resonators – lossless 1/4 wave transmission line (at 3 GHz $\lambda/4$ = 1 inch)

  Barium titanate gives $Q = 20{,}000$

- Quartz resonators – although the piezoelectric effect is smaller, quartz has exceptional mechanical and electrical stability. $Q \approx 10^4$ to 10^6.

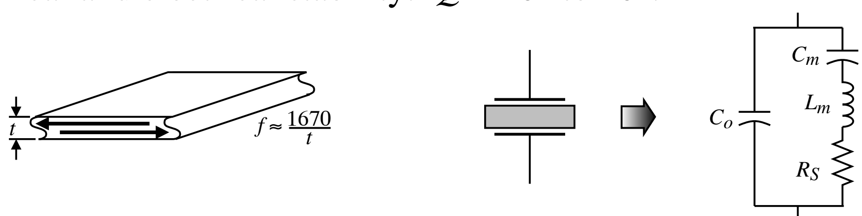


Illustration of Bulk Shear Mode Crystal Symbol and Model Fig010-05

$$R_S \approx \frac{5\text{x}10^8}{f_o} \text{ or}$$

$$R_S \approx \frac{5\text{x}10^8}{f_o} N^2$$

N = overtones

C_o = parallel plate capacitance, L_m and C_m = mechanical energy storage, R_S = losses

- Surface acoustic wave devices

  Surface waves avoid the undesired nonlinear behavior of bulk waves ($LiNbO_3$)

Frequency Translation – Mixers

Mixers require nonlinear or time-varying elements in order to provide frequency translation.

Mixer types:

- Multiplication – the output has only the sum and difference of the two input frequencies.
- Modulation – the output not only has the sum and differences of the two input frequencies, but many other frequencies

Mixer fundamentals:

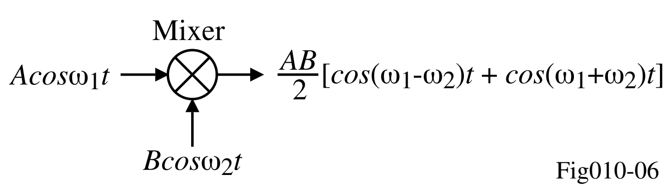


Fig010-06

- A lowpass filter is used to obtain the difference frequency and a highpass filter to obtain the sum frequency
- The mixer gain is given as $\frac{AB}{2}$
- A mixer is difficult to analyze because the output frequency is different from the input frequency.

Note: The signals into the mixer do not need to be sinusoidal.

Mixer Types

1.) Passive and active mixers

2.) Mixers are classified as whether the inputs are balanced (differential) or unbalanced (single-ended)

(1.) Single-ended - both ω_1 and ω_2 are single-ended

(2.) ω_1-Balanced - ω_1 is balanced and ω_1 is single-ended

(3.) ω_2 -Balanced - ω_2 is balanced and ω_1 is single-ended

(4.) Doubly-Balanced - Both the ω_1 and ω_2 are balanced

Comparison:

Mixer Type → Characteristic	Single-Ended	ω_1-Balanced	ω_2-Balanced	Doubly-Balanced
ω_1/ω_2 Isolation	Poor	Good	Poor	Good
ω_1/ω_2 Isolation	Poor	Poor	Good	Good
ω_1 Harmonic Rejection	None	Even	All	All
ω_2 Harmonic Rejection	None	All	Even	All
Single-tone Spurious Rejection	None	?	?	?
Two-tone 2nd-order product rejection	No	No	Yes	Yes

Frequency Translation – Frequency Dividers

1.) Flip-Flop Dividers

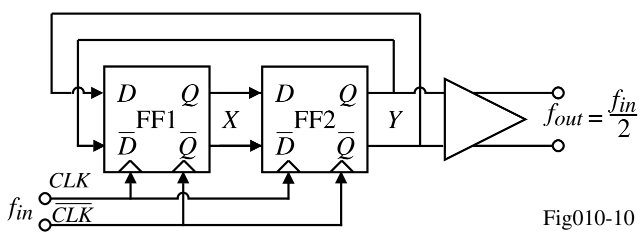


Fig010-10

Quadrature outputs are available at X and Y.

Need to load each flip-flop identically to insure the delays are equal.

2.) Miller Divider

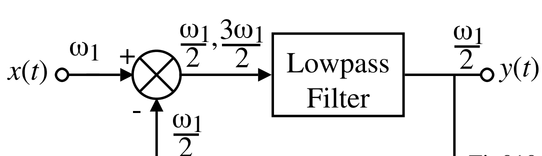


Fig010-11

If $x(t) = A_1 cos\omega_1 t$, then the signal going into the lowpass filter is given as,

$$A_2 cos\left(\frac{\omega_1 t}{2}\right) + A_2 cos\left(\frac{3\omega_1 t}{2}\right) \rightarrow y(t) = A_2 cos\left(\frac{\omega_1 t}{2}\right)$$

The filter cutoff frequency, f_c, should be $0.5f_1 < f_c < 1.5f_1$.

Frequency Translation – Frequency Multipliers

1.) Full-wave rectifier.

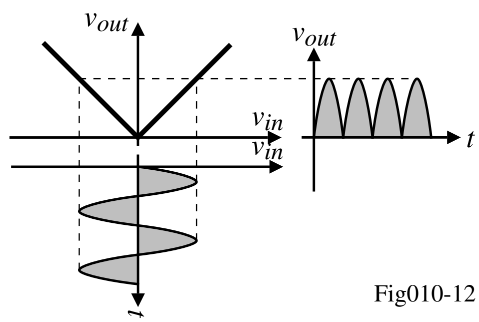


Fig010-12

2.) Phase locked loop.

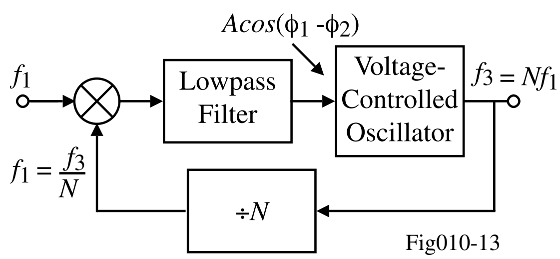


Fig010-13

Filters

Filters are used to discriminate against certain frequencies and to pass other frequencies.

Lowpass:

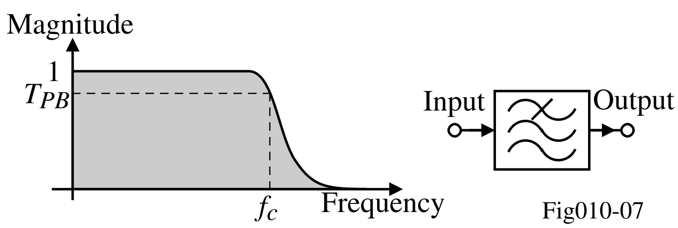


Fig010-07

Bandpass:

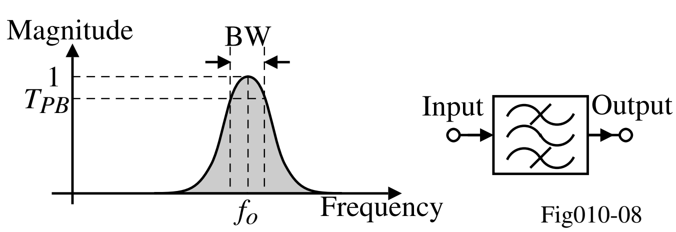


Fig010-08

Highpass:

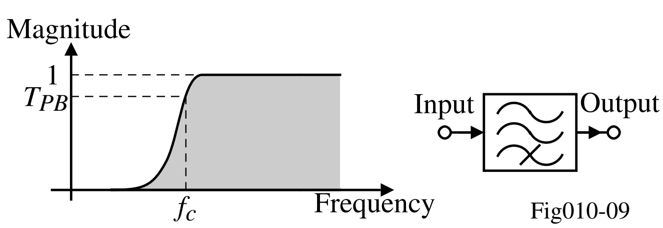


Fig010-09

Techniques for Frequency Synthesis

1.) Incoherent Synthesis – A relatively few reference frequencies are combined to generate many frequencies.

2.) Coherent Synthesis – A single reference frequency is used to generate many output frequencies.

- Coherent Direct Synthesis – Frequency mixers, frequency dividers, and frequency multipliers are used to generate many output frequencies. This method is also called arithmetic synthesis.
- Coherent Direct Digital Synthesis – Digital accumulators, ROMs, and digital-analog converters are used to generate a discrete-time approximation to a sine wave.
- Coherent Indirect Synthesis – Voltage controlled oscillators, mixers, phase locked loops (PLLs), frequency multipliers, and frequency dividers generate an output that has a definite relationship to a reference frequency.

Incoherent Synthesis

Example:

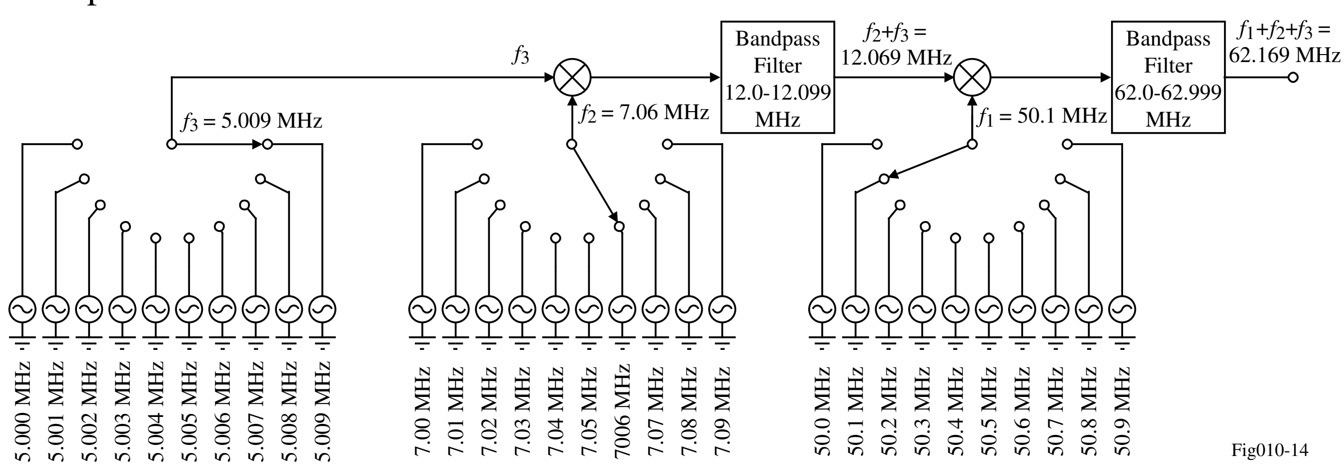


Fig010-14

- This synthesizer covers the frequency range of 62.000 to 62.999 MHz
- Thirty reference frequencies (crystals) are used to generate 1000 frequencies
- Minimizing spurious outputs generated in the mixers is important
- At one time, this synthesizer had the advantage of lowest cost, but now indirect digital PLL synthesizers are less expensive.

Coherent Direct Synthesis

Example:

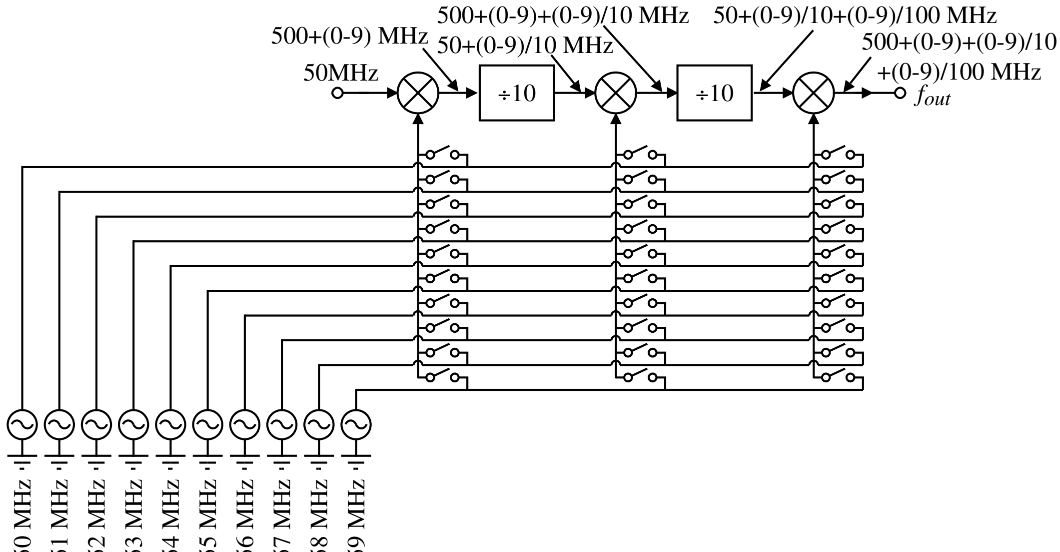


Fig010-15

Advantages:

- The speed of switching is high, typically ≤ 10μs
- The frequency resolution can be made very high without affecting switching speed

Disadvantages:

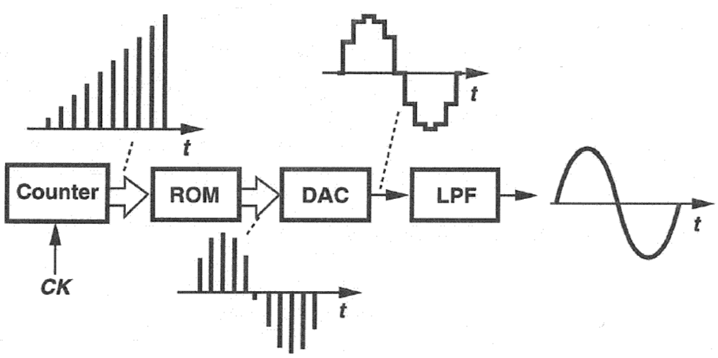
- Complex system is too expensive to build
- Large number of mixers increases the likelihood of spurious outputs

Coherent Direct Digital Synthesis (DDS)

DDS generates the signal in the digital domain and utilizes an A/D converter and filtering to reconstruct the waveform in the analog domain.

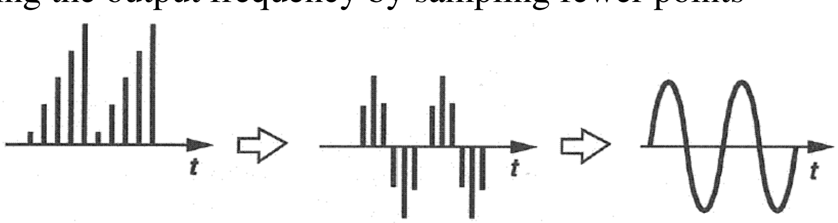
Illustration of the DDS principle:

Simple digital synthesis of a sine wave using a counter with N counts-



$$f_{out} = \frac{f_{clk}}{2^N}$$

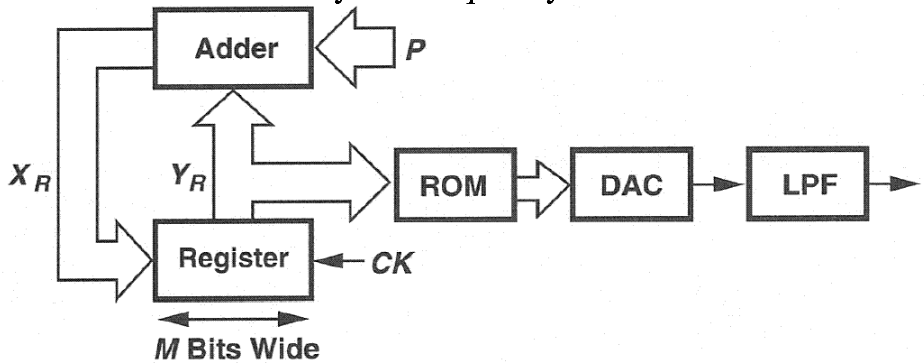
Increasing the output frequency by sampling fewer points-



$$f_{out}(\max) \approx \frac{f_{clk}}{2.5}$$

DDS – Continued

DDS using an accumulator to vary the frequency:



Operation:

The counter is implemented as an accumulator where a parallel-in, parallel-out M-bit register drives an adder in a feedback loop.

On every clock cycle,

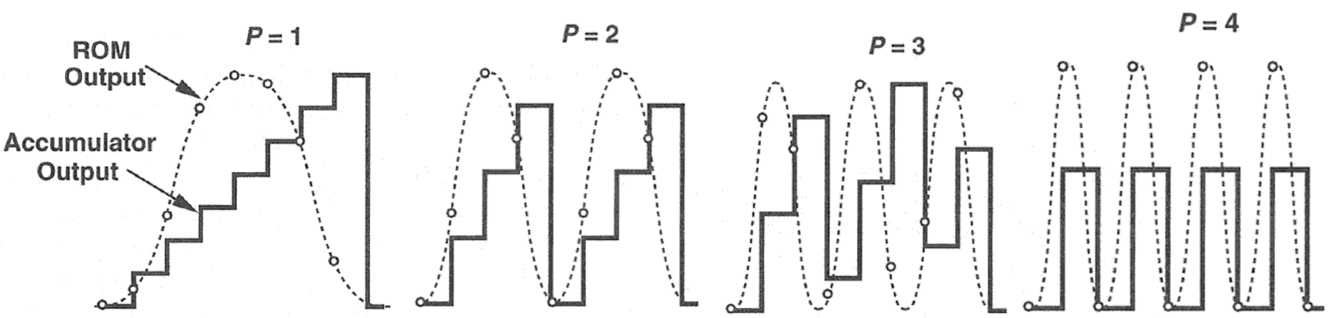
$$X_R(k) = Y_R(k\text{-}1) + P$$

When the register overflows, part of P appears as an increment in the new value of Y_R,

$$X_R(k) = Y_R(k\text{-}1) + P \text{ modulo } 2^M$$

DDS – Continued

Example of the previous DDS using an accumulator (M=3):



For P = 1, the register goes from 000 to 111. Clock period increments the output phase by $2\pi/8$.

For P = 2, the accumulator overflows after 110 and every other sample is read from the ROM causing the output phase to change every $2\pi/4$.

For P = 3, the accumulator output begins at 000 and overflows at 110,11, and 101 in the first, second, and third cycles, respectively.

For P = 4, four cycles of the sinusoid are generated by the Nyquist-rate sampling.

$$\therefore \quad f_{out} = P\frac{f_{CK}}{2^M} \quad \rightarrow \quad f_{out}(\min) = P\frac{f_{CK}}{2^M} \text{ and } f_{out}(\max) = P\frac{f_{CK}}{2}$$

DDS – Continued

Comments:

- D/A converter will introduce phase noise
- The DDS can be FM, PM or AM modulated
- The DDS can generate arbitrary waveforms
- The DDS is capable of fast switching between frequencies
- The DDS will generate spurs because the quantization error period changes between even and odd values of *P*. The spurs can be minimized to below 70dBc if the ROM is about 12 bits.
- DDS avoids the use of an analog VCO and achieves low phase noise
- DDS provides fine frequency steps (close channel spacing)
- DDS can provide continuous-phase channel switching at the output, an important property in some modulation schemes
- DDS allows direct modulation of the output signal in the digital domain
- DDS is restricted to lower frequencies (≈100 MHz) to avoid high power consumption

Coherent Indirect Synthesis

Function of a frequency synthesizer is to generate a frequency f_o from a reference frequency f_{ref}.

Block diagram:

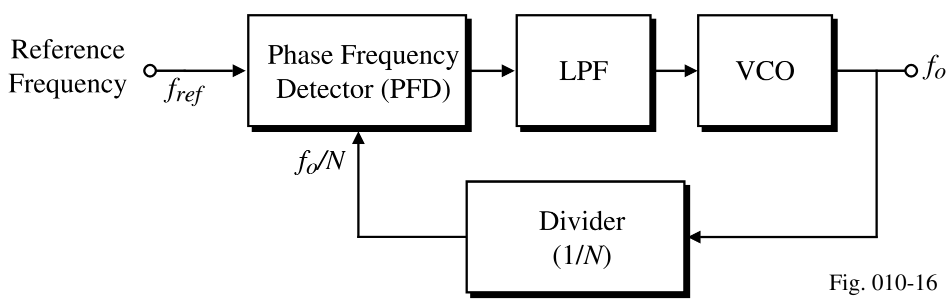


Fig. 010-16

Components:

Phase/frequency detector outputs a signal that is proportional to the difference between the frequency/phase of two input periodic signals.

The low-pass filter is use to reduce the phase noise and enhance the spectral purity of the output.

The voltage-controlled oscillator takes the filtered output of the PFD and generates an output frequency which is controlled by the applied voltage.

The divider scales the output frequency by a factor of *N*.

$$f_{ref} = \frac{f_o}{N} \quad \rightarrow \quad f_o = Nf_{ref}$$

Coherent Indirect Synthesis – Continued

This type of frequency synthesizer is probably the most popular approach today and is very compatible with integrated circuit technology.

Comments:

- Frequency step size is equal to f_{ref}. Thus, for small channel spacing, f_{ref}, is small which makes N large.
- Large N results in an increase in the in-band phase noise of the VCO signal by $20log(N)$.
- $f_o = N{\cdot}f_{ref}$
- The loop filter has a significant impact on the performance of the frequency synthesizer-
  - The bandwidth of the LPF is generally 5-10 larger than the reference frequency
  - The lower the bandwidth of the LPF, the less the phase noise
  - The higher the bandwidth of the LPF, the faster the switching time

The components of the above frequency synthesizer will be studied in much more detail in this course. You could say that this is a course on phase-locked loops.

Coherent Indirect Synthesis – Continued

A modification of the previous system to enhance tradeoffs.

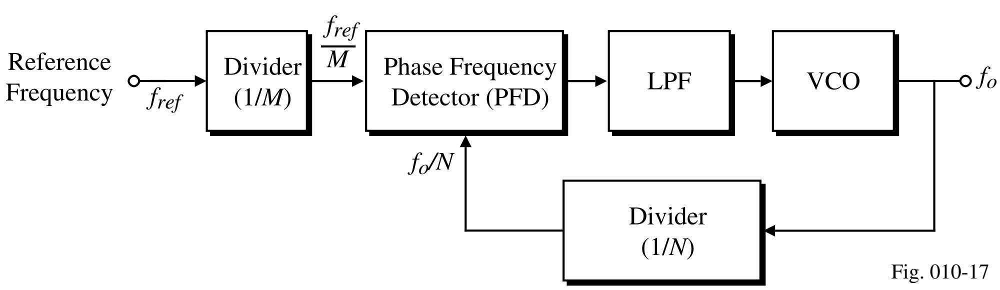


Fig. 010-17

The output frequency is equal to,

$$\frac{f_{ref}}{M} = \frac{f_o}{N} \rightarrow f_o = \frac{N}{M} f_{ref}$$

This gives more flexibility in the choice of f_{ref} and the bandwidth of the LPF.

Combination of Techniques

Combining the various approaches offers performance that could not otherwise be achieved by a single approach or technique.

Example of a DDS plus a coherent indirect synthesizer:

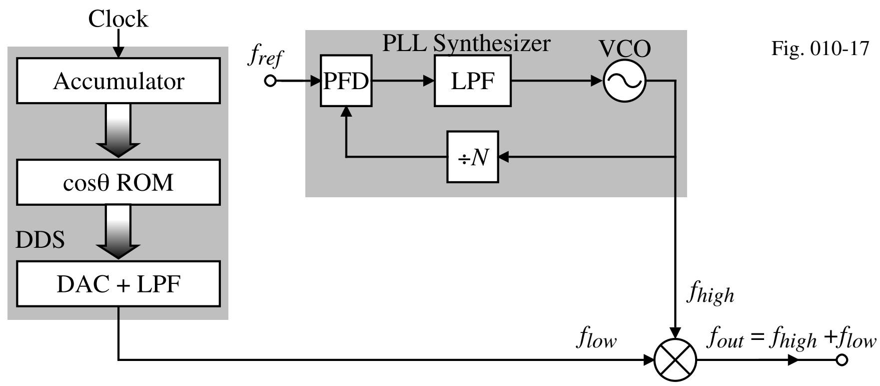


Fig. 010-17

Comments:

- The loop bandwidth can be optimized for noise since the output frequency can be changed rapidly and in small intervals by changing the DDS frequency, f_{low}.
- The technique suffers from a limited output frequency range due to the low value of f_{low}.
- If the purity requirements are high, the DAC needs to have a large number of bits and will be power hungry.

SUMMARY

- This course will focus on the analysis and design of frequency synthesizers implemented using both discrete and integrated circuit technology.
- The coherent indirect synthesis method (PLL approach) will be the primary type of frequency synthesizer considered.
- Course outline:
  - Introduction
  - Technology
  - PLLs
    - PFDs
    - Filters
    - VCOs
    - Dividers
  - Frequency synthesizers
  - Clock and data recovery circuits
  - Applications of frequency synthesizers