

Key Design Features

- Synthesizable, technology independent IP Core for FPGA, ASIC and SoC
- Supplied as human readable VHDL (or Verilog) source code
- 16-bit signed output data samples
- 32-bit phase accumulator (tuning word)
- 32-bit phase shift feature
- Phase resolution of $2\pi / 2^{16}$
- Frequency resolution of $F_s / 2^{32}$ (F_s = sample frequency)
- Phase dithering option for improved SFDR
- ≈ 100 dB SNR and > 110 dB SFDR (with phase dithering enabled)
- Simultaneous SIN, COS, square and sawtooth outputs
- Optimized quarter-wave LUT for reduced area footprint
- Sample rates of 350 MHz¹

Applications

- Digital oscillators and phase-locked loops
- Digital modulation/demodulation
- Digital up/down converters and mixers
- Generation of quadrature (complex) signals
- Versatile waveform generation

Pin-out Description

Pin name	I/O	Description	Active state
clk	in	Sample clock	rising edge
reset	in	Asynchronous reset	low
en	in	clock enable	high
phase_inc [31:0]	in	Phase increment as an unsigned 32-bit number	data
phase_shift [31:0]	in	Phase shift as an unsigned 32-bit number	data
sin_out [15:0]	out	Sine wave output (16-bit signed number)	data
cos_out [15:0]	out	Cosine wave output (16-bit signed number)	data
squ_out [15:0]	out	Square wave output (16-bit signed number)	data
saw_out [15:0]	out	Sawtooth wave output (16-bit signed number)	data

¹ Xilinx® 7-series FPGAs used as a benchmark

Block Diagram

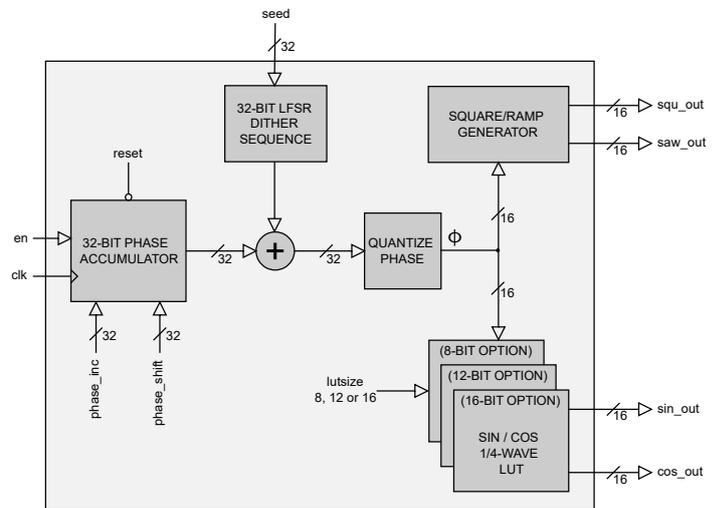


Figure 1: Direct Digital Synthesizer architecture

Generic Parameters

Generic name	Description	Type	Valid range
dithering	Enable phase dithering	boolean	TRUE/FALSE
lutsize	Use an 8, 12 or 16-bit Look-up table (Effective size)	integer	8, 16 or 12
seed	Seed for random number generator	std_logic vector	$0 < \text{seed} < 2^{32}$

General Description

The DDS IP Core is a high-precision Direct Digital Synthesizer² used for the generation of periodic waveforms. On each rising-edge of the sample clock and when the clock-enable is high, the phase in the phase-accumulator is incremented by the value *phase_inc*. This phase is quantized to 16-bits and passed as an address to a look-up table which converts the phase into a waveform.

To save resources, the look-up table is implemented as a quarter sine wave (16384 x 15-bit samples). These samples are manipulated to generate 65536 x 16-bit samples over the range 0 to 2Pi. By setting the generic parameter *lutsize* to 12 or 8, the size of the LUT can be reduced further to (1024 x 11-bit) or (64 x 7-bit) if required. The general architecture of the DDS circuit is shown in Figure 1 above.

In addition to the quadrature outputs *sin_out* and *cos_out*, the DDS also provides square wave and sawtooth outputs: *squ_out* and *saw_out*. All output values are 16-bit signed numbers.

² Also known as a Numerically Controlled Oscillator (NCO)

Source File Description

All source files are provided as text files coded in VHDL. The following table gives a brief description of each file.

Source file	Description
sincos_lut16.vhd	SIN/COS look-up table (16-bit equivalent version)
sincos_lut12.vhd	SIN/COS look-up table (12-bit equivalent version)
sincos_lut8.vhd	SIN/COS look-up table (8-bit equivalent version)
dds.vhd	Top-level component
dds_bench.vhd	Top-level test bench

Functional Testing

An example VHDL testbench is provided for use in a suitable VHDL simulator. The compilation order of the source code is as follows:

1. sincos_lut16.vhd
2. sincos_lut12.vhd
3. sincos_lut8.vhd
4. dds.vhd
5. dds_bench.vhd

The VHDL testbench instantiates the DDS component and the user may modify the phase increment and generic parameters in order to generate the desired output waveform. The example provided generates a 2.73 MHz waveform with a 100 MHz sample clock.

The simulation must be run for at least 3 ms during which time the DDS will output the SIN, COS, square and sawtooth waveforms. Output samples are captured in the text file *dds_out.txt*. Figures 3 to 6 show plots of the resulting waveforms.

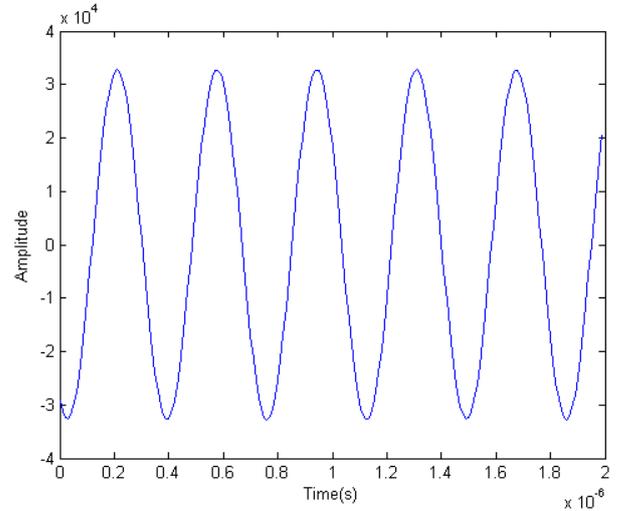


Figure 3: SIN waveform output (2.73 MHz)

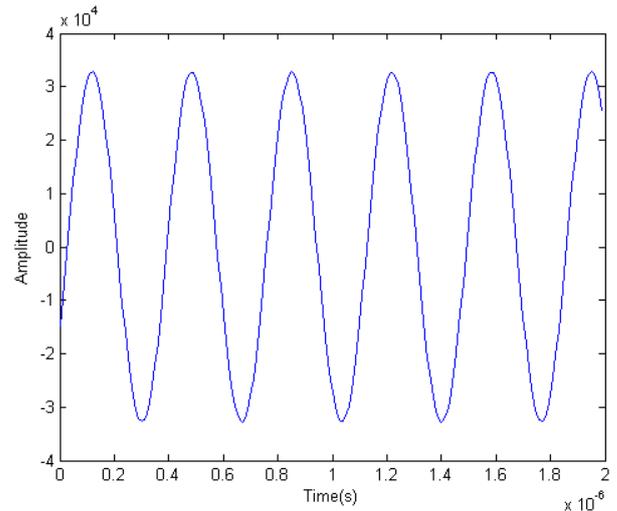


Figure 4: COS waveform output (2.73 MHz)

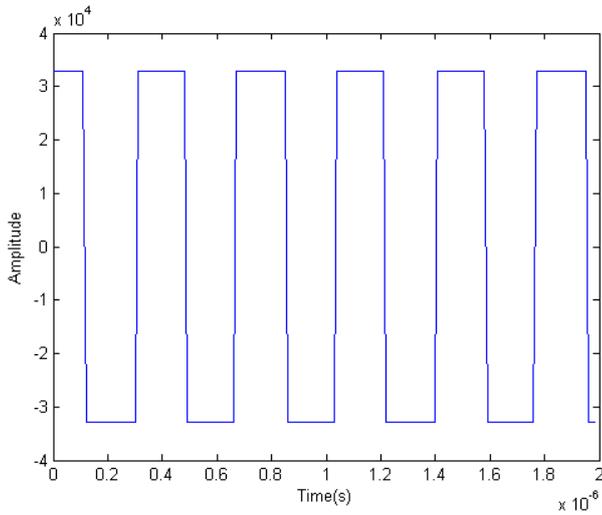


Figure 5: Square waveform output (2.73 MHz)

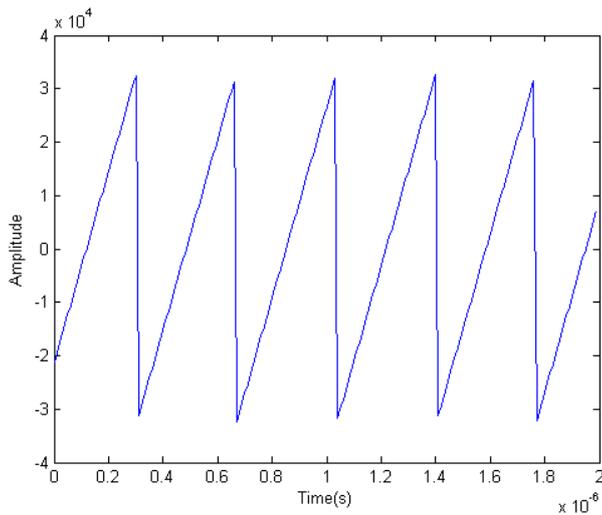


Figure 6: Sawtooth waveform output (2.73 MHz)

Performance

The following plots demonstrate the effect of phase dithering on the output power spectra. The plots show the mean-squared power estimate of the SIN output samples for a 100MHz sample clock and a 2.73 MHz output waveform. The size of the LUT has been set to 16-bits.

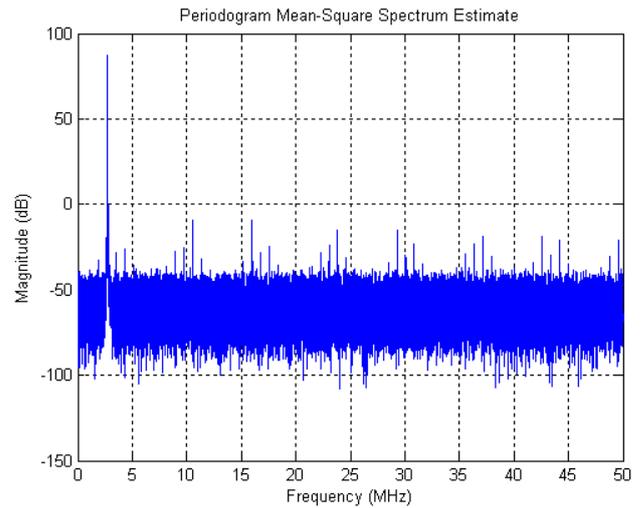


Figure 7: Single 2.73 MHz tone - dithering disabled

The SFDR for the non phase-dithered case (Figure 7) exhibits an SFDR of 96.3 dB with the largest magnitude spur of -9.1 dB at around 16 MHz.

Figure 8 shows the same 2.73 MHz tone with phase-dithering enabled. The SFDR is 114.9 dB with the largest magnitude spur of -27.7 dB at around 8 MHz. This is an improvement in SFDR of 18.6 dB.

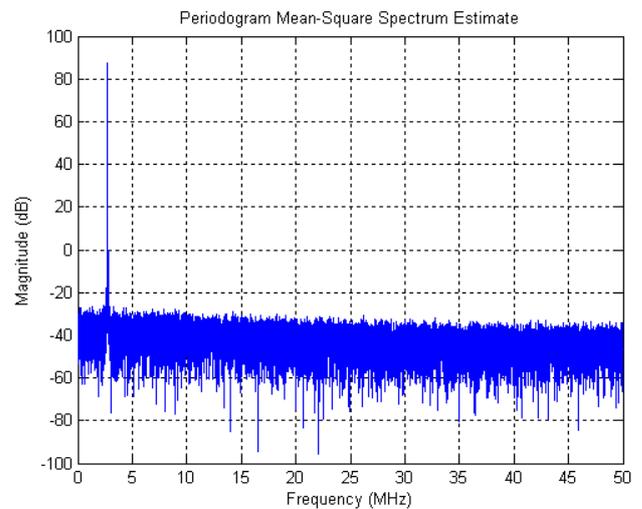


Figure 8: Single 2.73 MHz tone - dithering enabled

The following table summarizes the estimated values for SFDR and SNR for the 16-bit, 12-bit and 8-bit LUT versions of the DDS.

DDS PERFORMANCE ESTIMATES

Version	SNR	SFDR (no dithering)	SFDR (with dithering)
16-bit LUT	~100 dB	~95 dB	~115 dB
12-bit LUT	~75 dB	~70 dB	~90 dB
8-bit LUT	~33 dB	~60 dB	~62 dB

Synthesis and Implementation

The files required for synthesis and the design hierarchy are shown below:

- dds.vhd
 - sincos_lut16.vhd
 - sincos_lut12.vhd
 - sincos_lut8.vhd

The VHDL core is designed to be technology independent. However, as a benchmark, synthesis results have been provided for the Xilinx® 7-series FPGAs. Synthesis results for other FPGAs and technologies can be provided on request.

Note that setting the lutsize to 8-bits will result in a very tiny LUT implementation and will greatly reduce the internal RAM resources required. This will, however, be at the cost of reduced performance (SNR and SFDR). Setting the LUT size to 12-bits is a good compromise between resource use and performance. The 16-bit LUT uses the most resources but gives the best possible performance. Likewise, the implementation will be smaller if the dithering function is disabled, but again this will also be at a performance cost.

Trial synthesis results are shown with the generic parameters set to: dithering = true, lutsize = 12, seed = 0x7AF1093D.

Resource usage is specified after Place and Route.

XILINX® 7-SERIES FPGAS

Resource type	Artix-7	Kintex-7	Virtex-7
Slice Register	262	262	262
Slice LUTs	417	417	417
Block RAM	0	0	0
DSP48	0	0	0
Occupied Slices	152	147	142
Clock freq. (approx)	250 MHz	350 MHz	450 MHz+

Revision History

Revision	Change description	Date
1.0	Initial revision	22/05/2008
1.1	Modified key design features	06/11/2008
1.2	Added support for a smaller 12-bit LUT implementation. Updated synthesis results	17/01/2012
1.3	Added support for phase shifts. Updated synthesis results for Xilinx® 6 series FPGAs	08/06/2012
1.4	Updated block diagram	03/04/2014
1.5	Added the 8-bit LUT option. Updated synthesis results for Xilinx® 7 series FPGAs	08/10/2019