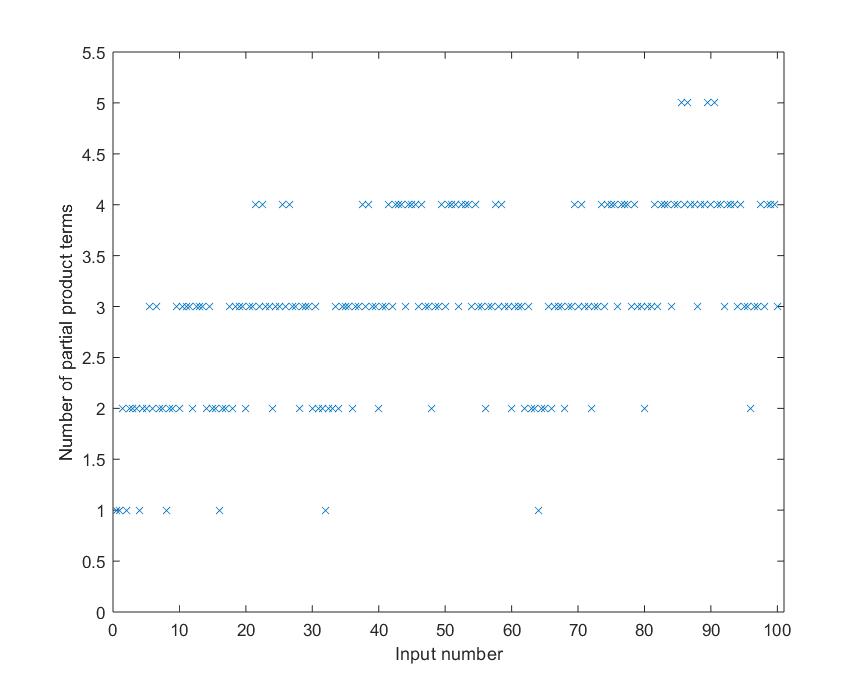
# Problem 1

## Result

Total sum for +0.5 - +100.00 = 605



## numppterms.m

function [mpp] = numppterms(num)

mpp = 0;

rem = num;

while (rem ~= 0 && mpp < 10)

for i = -1:10

if 2^i >= abs(rem)

mpp = mpp + 1;

if (2^i - abs(rem) < abs(rem) - 2^(i-1))

rem = abs(rem) - 2^i;

else

rem = abs(rem) - 2^(i-1);

end

break;

end

end

end

end

# Problem 2

## Matlab output for unscaled coefficients

Scale 1.000000 Using coefficients [ 17 -90 241 902 241 -90 17]

coef #1 17, 2 partial products

coef #2 -90, 4 partial products

coef #3 241, 3 partial products

coef #4 902, 4 partial products

coef #5 241, 3 partial products

coef #6 -90, 4 partial products

coef #7 17, 2 partial products

In total, need 22 partial products

## Matlab output for scaled coefficients

Scale 0.532000 Using coefficients [ 9 -48 128 480 128 -48 9]

coef #1 9, 2 partial products

coef #2 -48, 2 partial products

coef #3 128, 1 partial products

coef #4 480, 2 partial products

coef #5 128, 1 partial products

coef #6 -48, 2 partial products

coef #7 9, 2 partial products

In total, need 12 partial products

## Matlab code

clear;

addpath('../part1/') %add numppterms

%fir

%coef = [17 -90 241 902 241 -90 17]

%pps 2 4 3 4 3 4 2

% +16 -64 +256 +1024 +256 -64 +16

% +1 -32 -16 -128 -16 -32 +1

% +4 -1 +4 -1 +4

% +2 -2 +2

%original coefficients

coef = [17 -90 241 902 241 -90 17];

%scaling factor

%scale = 1;

scale = 0.532; %12 pps, coef\_r will be [9 -48 128 480 128 -48 9]

%rounded coedficients

coef\_r = round( coef \* scale );

fprintf("Scale %f Using coefficients [", scale);

fprintf(" %d", coef\_r);

fprintf("]\n");

%total number of partial products for FIR

total = 0;

%calculation

for fircoef = 1:7

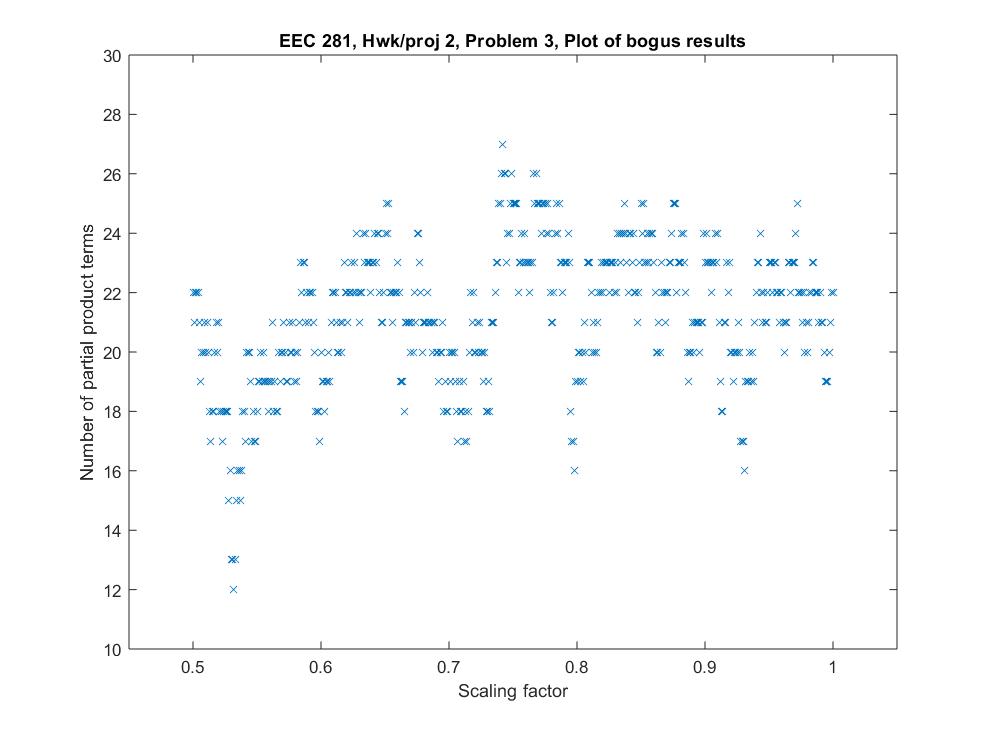
total = total + numppterms(coef\_r(fircoef));

fprintf("coef #%d %d, %d partial products\n", fircoef, coef\_r(fircoef), numppterms(coef\_r(fircoef)));

end

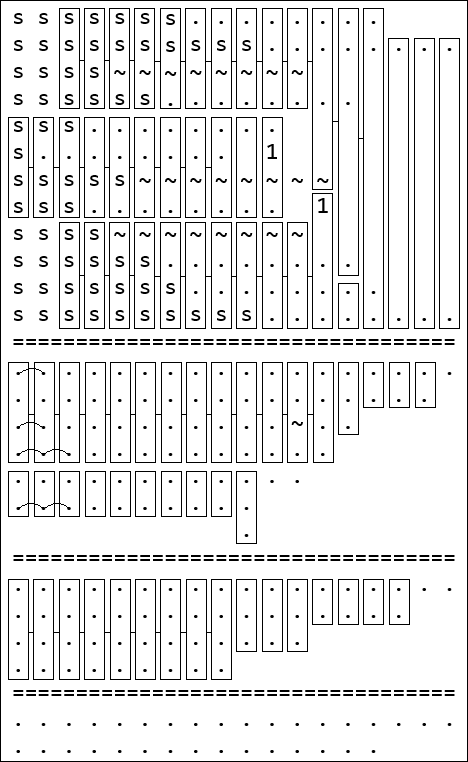
fprintf("In total, need %d partial products\n", total);

## Bogus plot



## Dot diagram

[ ] – 4:2 adder, [ ] – 3:2 adder, [ ] – half adder, ”.” – signal, “~” – inverted signal, “s” – sign extend, ark – right-to-left signal copy to reduce number of adders due to same inputs.

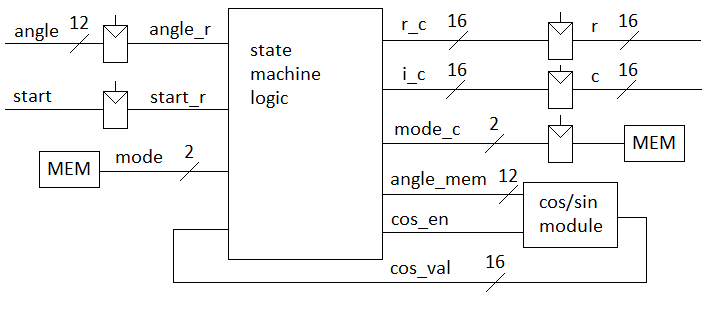


# Problem 3

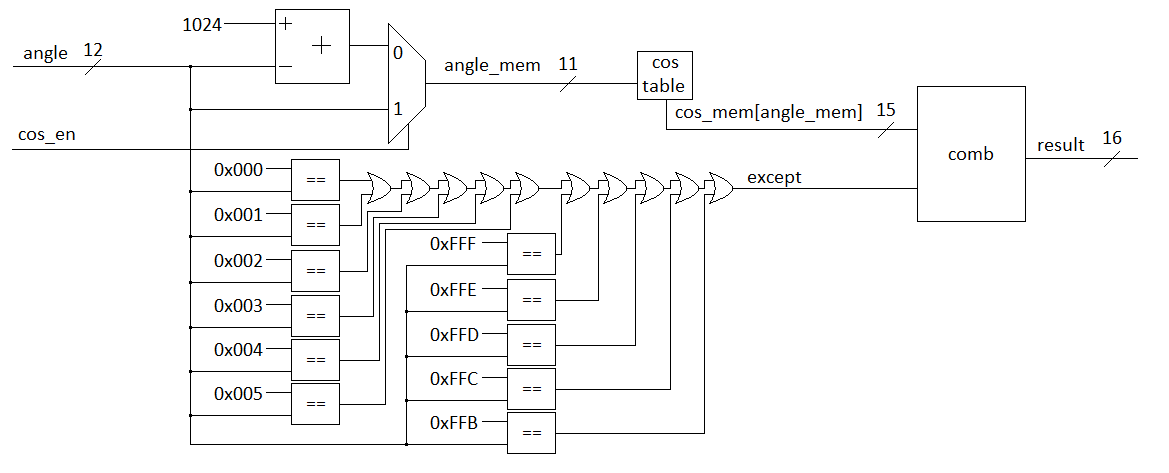
## Part 1

|  |  |
| --- | --- |
| Clock period | Total cell area |
| 4ns | 162.792004 |
| 1ns | 162.792004 |
| 20ns | 162.792004 |

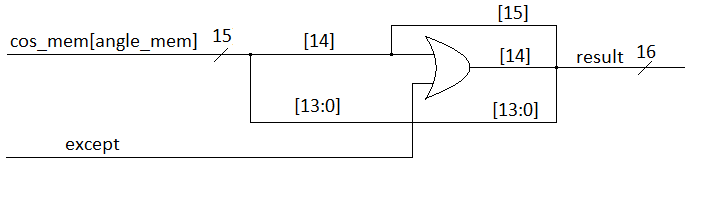
Top-level diagram:



“cos/sin module” diagram:



“comb” module diagram (applies exception for result):



Energy\_diff / Energy\_data0 = 10\*log(0.000002/4096.020943) = -83.11dB

Difff.m output:

max(data0-data1) = +0.000031 +0.000031i = +3.05034e-05 +3.05034e-05i

min(data0-data1) = -0.000031 -0.000031i = -3.05034e-05 -3.05034e-05i

max(data0/data1) = -Inf -Infi

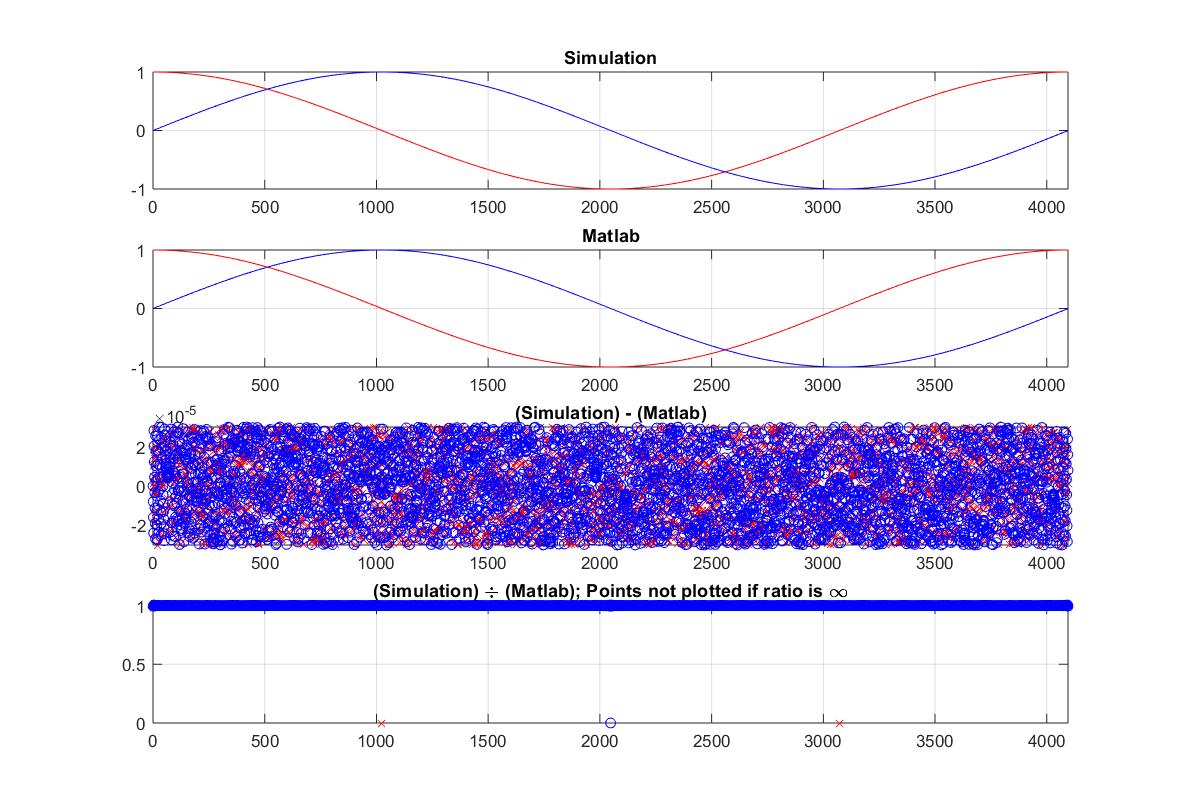
min(data0/data1) = +Inf +Infi

approx separated mean(data0/data1) = +0.999508+ +0.999508i

Energy\_data0 = 4096.020943

Energy\_diff = 0.000002

Energy\_data0/Energy\_diff = 1653952521.828711 = 92.185230dB



### Code:

/\*

Top level for complex number generator

\*/

//cos function lookup table

//full precision for angle [0 .. 360) degrees

`timescale 1ns/10ps

module cos(

input cos\_en,

input [11:0] angle,

output reg [15:0] result

);

reg except;

reg [14:0] cos\_mem [4095:0];

reg [11:0] angle\_mem;

initial begin

result = 16'b0000\_0000\_0000\_0000;

//load values to memory

cos\_mem[12'b000000000000] = 15'b000000000000000;

cos\_mem[12'b000000000001] = 15'b000000000000000;

cos\_mem[12'b000000000010] = 15'b000000000000000;

cos\_mem[12'b000000000011] = 15'b000000000000000;

cos\_mem[12'b000000000100] = 15'b000000000000000;

cos\_mem[12'b000000000101] = 15'b000000000000000;

cos\_mem[12'b000000000110] = 15'b011111111111111;

cos\_mem[12'b000000000111] = 15'b011111111111111;

cos\_mem[12'b000000001000] = 15'b011111111111111;

cos\_mem[12'b000000001001] = 15'b011111111111110;

cos\_mem[12'b000000001010] = 15'b011111111111110;

cos\_mem[12'b000000001011] = 15'b011111111111110;

cos\_mem[12'b000000001100] = 15'b011111111111101;

cos\_mem[12'b000000001101] = 15'b011111111111101;

cos\_mem[12'b000000001110] = 15'b011111111111100;

//<Many lines removed>

cos\_mem[12'b111111110001] = 15'b011111111111100;

cos\_mem[12'b111111110010] = 15'b011111111111100;

cos\_mem[12'b111111110011] = 15'b011111111111101;

cos\_mem[12'b111111110100] = 15'b011111111111101;

cos\_mem[12'b111111110101] = 15'b011111111111110;

cos\_mem[12'b111111110110] = 15'b011111111111110;

cos\_mem[12'b111111110111] = 15'b011111111111110;

cos\_mem[12'b111111111000] = 15'b011111111111111;

cos\_mem[12'b111111111001] = 15'b011111111111111;

cos\_mem[12'b111111111010] = 15'b011111111111111;

cos\_mem[12'b111111111011] = 15'b000000000000000;

cos\_mem[12'b111111111100] = 15'b000000000000000;

cos\_mem[12'b111111111101] = 15'b000000000000000;

cos\_mem[12'b111111111110] = 15'b000000000000000;

cos\_mem[12'b111111111111] = 15'b000000000000000;

end

always @(angle or cos\_en) begin

//cos/sin selection

if (cos\_en == 1'b1)

//compute cos(angle)

angle\_mem = angle;

else

//compute sin(angle) = cos (pi/2 - angle)

angle\_mem = 12'b0100\_0000\_0000 - angle;

//exception (when need to return == +1.0)

except = (angle\_mem == 12'b0000\_0000\_0000);

except = except || (angle\_mem == 12'b0000\_0000\_0001);

except = except || (angle\_mem == 12'b0000\_0000\_0010);

except = except || (angle\_mem == 12'b0000\_0000\_0011);

except = except || (angle\_mem == 12'b0000\_0000\_0100);

except = except || (angle\_mem == 12'b0000\_0000\_0101);

except = except || (angle\_mem == 12'b1111\_1111\_1011);

except = except || (angle\_mem == 12'b1111\_1111\_1100);

except = except || (angle\_mem == 12'b1111\_1111\_1101);

except = except || (angle\_mem == 12'b1111\_1111\_1111);

except = except || (angle\_mem == 12'b1111\_1111\_1110);

//output

result = {cos\_mem[angle\_mem][14], cos\_mem[angle\_mem][14] | except, cos\_mem[angle\_mem][13:0]};

end

endmodule

module compl(

input [11:0] angle,

input start,

input clk,

input reset,

output reg [15:0] r,

output reg [15:0] i

);

parameter IDLE = 2'b00;

parameter COS = 2'b01;

parameter SIN = 2'b10;

reg [1:0] mode, mode\_c;

reg [11:0] angle\_mem, angle\_r;

reg [15:0] r\_c, i\_c;

wire [15:0] cos\_val;

reg cos\_en, start\_r;

initial begin

mode = IDLE;

mode\_c = IDLE;

angle\_mem = 12'b0000\_0000\_0000;

// angle\_r = 12'b0000\_0000\_0000;

r\_c = 16'b0000\_0000\_0000\_0000;

i\_c = 16'b0000\_0000\_0000\_0000;

cos\_en = 1'b0;

// start\_r = 1'b0;

end

cos cos\_mem (.angle (angle\_r), .cos\_en(cos\_en), .result(cos\_val));

//State Machine

always @(angle\_r or start\_r or mode) begin

mode\_c = mode;

case(mode)

IDLE: begin

if (start\_r == 1'b1) begin

mode\_c = COS;

cos\_en = mode\_c[0];

angle\_mem = angle\_r;

end

end

COS: begin

r\_c = cos\_val;

mode\_c = SIN;

cos\_en = mode\_c[0];

end

SIN: begin

i\_c = cos\_val;

mode\_c = IDLE;

end

default: begin

mode\_c = IDLE;

end

endcase

end

//output FFlop

always @(posedge clk or posedge reset) begin

if (reset == 1'b1) begin

r <= #1 16'b0000\_0000\_0000\_0000;

i <= #1 16'b0000\_0000\_0000\_0000;

mode <= #1 IDLE;

angle\_r <= #1 12'b0000\_0000\_0000;

start\_r <= #1 1'b0;

end else begin

r <= #1 r\_c;

i <= #1 i\_c;

mode <= #1 mode\_c;

angle\_r <= #1 angle;

start\_r <= #1 start;

end

end

endmodule

### Testbench:

`timescale 1ns/10ps

module tbench();

reg [11:0] angle;

integer file;

wire [15:0] comp\_r;

wire [15:0] comp\_i;

reg clk, start, rst;

integer count = 0;

compl C1 (

.angle (angle),

.start (start),

.clk (clk),

.reset (rst),

.r (comp\_r),

.i (comp\_i)

);

initial begin

$recordfile("mult\_test");

$recordvars(tbench);

file = $fopen("complex\_result.m", "w");

$fwrite(file, "output = [\n");

angle = 12'b0000\_0000\_0000;

clk = 1'b0;

start = 1'b0;

rst = 1'b1;

#25;

angle = 12'b0000\_0000\_0000;

rst = 1'b0;

start = 1'b1;

count = 3;

end

//clock

always begin

#10;

clk = ~clk;

end

//tests

always @(posedge clk) begin

#2;

if (rst == 1'b0) begin

start = 1'b0;

if (count != 0) begin

count = count - 1;

end else begin

//write result to file

$fwrite(file, "%d %d %d;\n", angle, comp\_r, comp\_i);

//update angle or exit

if (angle == 12'b111111111111) begin

$fwrite(file, "];\n");

$fclose(file);

$finish;

end else begin

angle = angle + 1;

start = 1'b1;

count = 3;

end

end

end

end

endmodule

### Area results:

Clk 1ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:31:13 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 133

Number of cells: 76

Number of combinational cells: 56

Number of sequential cells: 20

Number of macros/black boxes: 0

Number of buf/inv: 8

Number of references: 14

Combinational area: 64.372000

Buf/Inv area: 4.256000

Noncombinational area: 98.420003

Macro/Black Box area: 0.000000

Net Interconnect area: undefined (Wire load has zero net area)

Total cell area: 162.792004

Total area: undefined

1

Clk 4ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:35:20 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 133

Number of cells: 76

Number of combinational cells: 56

Number of sequential cells: 20

Number of macros/black boxes: 0

Number of buf/inv: 8

Number of references: 14

Combinational area: 64.372000

Buf/Inv area: 4.256000

Noncombinational area: 98.420003

Macro/Black Box area: 0.000000

Net Interconnect area: undefined (Wire load has zero net area)

Total cell area: 162.792004

Total area: undefined

1

Clk 20ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:34:04 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 133

Number of cells: 76

Number of combinational cells: 56

Number of sequential cells: 20

Number of macros/black boxes: 0

Number of buf/inv: 8

Number of references: 14

Combinational area: 64.372000

Buf/Inv area: 4.256000

Noncombinational area: 98.420003

Macro/Black Box area: 0.000000

Net Interconnect area: undefined (Wire load has zero net area)

Total cell area: 162.792004

Total area: undefined

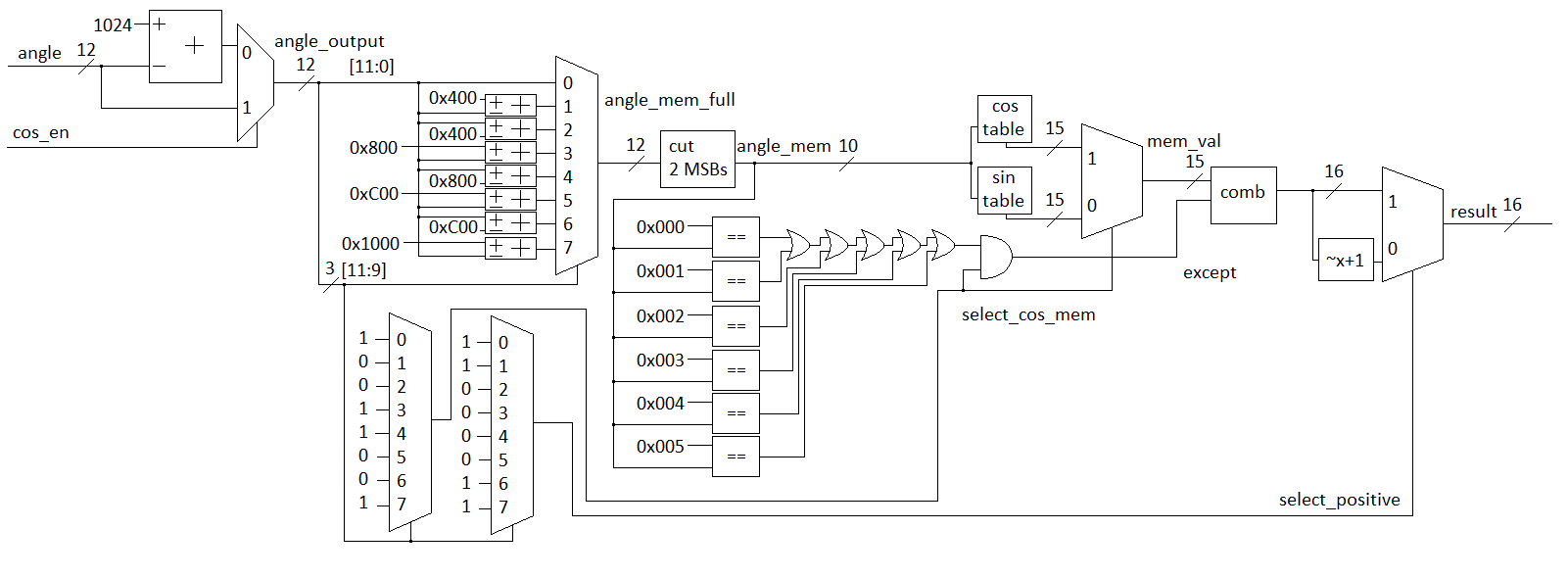
1

## Part 2

|  |  |
| --- | --- |
| Clock period | Total cell area |
| 4ns | 219.450003 |
| 1ns | 219.450003 |
| 20ns | 219.450003 |

Top-level design is the same as in part 1.

“cos/sin module” diagram:



“Comb” module is the same as in part 1.

Energy\_diff / Energy\_data0 = 10\*log(0.000002/4096.020943) = -83.113dB

Difff.m output:

max(data0-data1) = +0.000031 +0.000031i = +3.05034e-05 +3.05034e-05i

min(data0-data1) = -0.000031 -0.000031i = -3.05034e-05 -3.05034e-05i

max(data0/data1) = -Inf -Infi

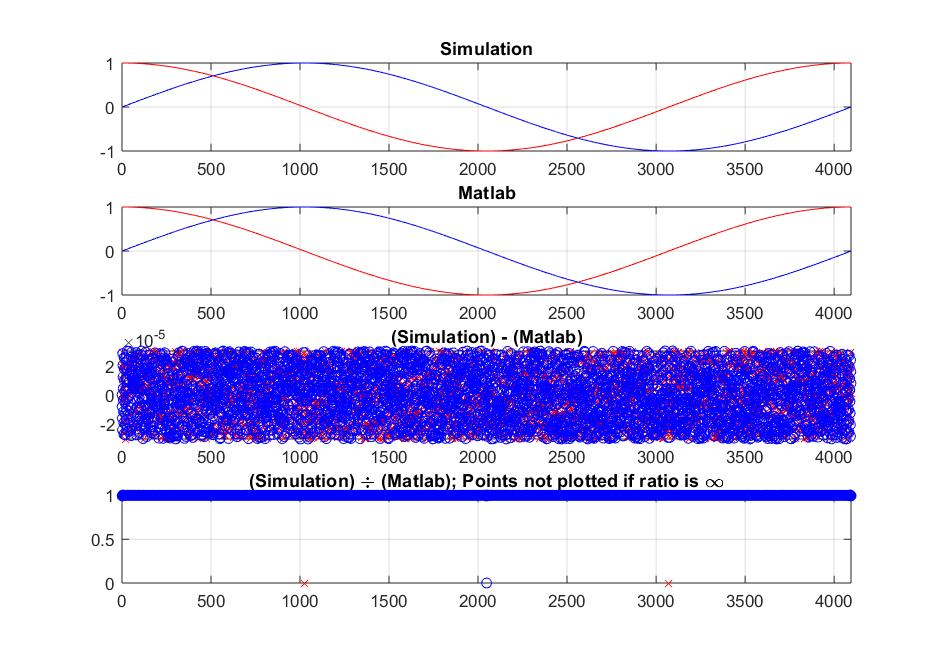
min(data0/data1) = +Inf +Infi

approx separated mean(data0/data1) = +0.999508+ +0.999508i

Energy\_data0 = 4096.020943

Energy\_diff = 0.000002

Energy\_data0/Energy\_diff = 1653952521.828711 = 92.185230dB



### Code:

/\*

Top level for complex number generator

\*/

//cos function lookup table

//full precision and [0 .. 45) degrees

`timescale 1ns/10ps

module cos(

input cos\_en,

input [11:0] angle, //full angle

output reg [15:0] result

);

reg except;

reg [14:0] cos\_mem [512:0];

reg [14:0] sin\_mem [512:0];

reg [9:0] angle\_mem; //memory address

//logic variables

reg select\_cos\_mem;

reg select\_positive;

reg [11:0] angle\_output, angle\_mem\_full;

reg [14:0] mem\_val;

initial begin

//defaults

result = 16'b0000\_0000\_0000\_0000;

mem\_val = 15'b000\_0000\_0000\_0000;

angle\_output = 12'b0000\_0000\_0000;

angle\_mem\_full = 12'b0000\_0000\_0000;

select\_cos\_mem = 1'b0;

select\_positive = 1'b1;

//load values to memory;

cos\_mem[10'b0000000000] = 15'b000000000000000; sin\_mem[10'b0000000000] = 15'b000000000000000;

cos\_mem[10'b0000000001] = 15'b000000000000000; sin\_mem[10'b0000000001] = 15'b000000000011001;

cos\_mem[10'b0000000010] = 15'b000000000000000; sin\_mem[10'b0000000010] = 15'b000000000110010;

cos\_mem[10'b0000000011] = 15'b000000000000000; sin\_mem[10'b0000000011] = 15'b000000001001011;

cos\_mem[10'b0000000100] = 15'b000000000000000; sin\_mem[10'b0000000100] = 15'b000000001100101;

cos\_mem[10'b0000000101] = 15'b000000000000000; sin\_mem[10'b0000000101] = 15'b000000001111110;

cos\_mem[10'b0000000110] = 15'b011111111111111; sin\_mem[10'b0000000110] = 15'b000000010010111;

cos\_mem[10'b0000000111] = 15'b011111111111111; sin\_mem[10'b0000000111] = 15'b000000010110000;

cos\_mem[10'b0000001000] = 15'b011111111111111; sin\_mem[10'b0000001000] = 15'b000000011001001;

cos\_mem[10'b0000001001] = 15'b011111111111110; sin\_mem[10'b0000001001] = 15'b000000011100010;

cos\_mem[10'b0000001010] = 15'b011111111111110; sin\_mem[10'b0000001010] = 15'b000000011111011;

cos\_mem[10'b0000001011] = 15'b011111111111110; sin\_mem[10'b0000001011] = 15'b000000100010100;

cos\_mem[10'b0000001100] = 15'b011111111111101; sin\_mem[10'b0000001100] = 15'b000000100101110;

cos\_mem[10'b0000001101] = 15'b011111111111101; sin\_mem[10'b0000001101] = 15'b000000101000111;

cos\_mem[10'b0000001110] = 15'b011111111111100; sin\_mem[10'b0000001110] = 15'b000000101100000;

//<Many lines removed>

cos\_mem[10'b0111110010] = 15'b010111000110111; sin\_mem[10'b0111110010] = 15'b010110001000110;

cos\_mem[10'b0111110011] = 15'b010111000100110; sin\_mem[10'b0111110011] = 15'b010110001011000;

cos\_mem[10'b0111110100] = 15'b010111000010101; sin\_mem[10'b0111110100] = 15'b010110001101010;

cos\_mem[10'b0111110101] = 15'b010111000000011; sin\_mem[10'b0111110101] = 15'b010110001111100;

cos\_mem[10'b0111110110] = 15'b010110111110010; sin\_mem[10'b0111110110] = 15'b010110010001110;

cos\_mem[10'b0111110111] = 15'b010110111100000; sin\_mem[10'b0111110111] = 15'b010110010100000;

cos\_mem[10'b0111111000] = 15'b010110111001111; sin\_mem[10'b0111111000] = 15'b010110010110010;

cos\_mem[10'b0111111001] = 15'b010110110111101; sin\_mem[10'b0111111001] = 15'b010110011000100;

cos\_mem[10'b0111111010] = 15'b010110110101011; sin\_mem[10'b0111111010] = 15'b010110011010110;

cos\_mem[10'b0111111011] = 15'b010110110011010; sin\_mem[10'b0111111011] = 15'b010110011101000;

cos\_mem[10'b0111111100] = 15'b010110110001000; sin\_mem[10'b0111111100] = 15'b010110011111010;

cos\_mem[10'b0111111101] = 15'b010110101110110; sin\_mem[10'b0111111101] = 15'b010110100001100;

cos\_mem[10'b0111111110] = 15'b010110101100101; sin\_mem[10'b0111111110] = 15'b010110100011110;

cos\_mem[10'b0111111111] = 15'b010110101010011; sin\_mem[10'b0111111111] = 15'b010110100101111;

cos\_mem[10'b1000000000] = 15'b010110101000001; sin\_mem[10'b1000000000] = 15'b010110101000001;

end

always @(angle or cos\_en) begin

//cos/sin selection for output

if (cos\_en == 1'b1)

//compute cos(angle)

angle\_output = angle;

else

//compute sin(angle) = cos (pi/2 - angle)

angle\_output = 11'b100\_0000\_0000 - angle;

//choose cos/sin mem bank

case (angle\_output[11:9])

3'b000: begin //0 - 45

angle\_mem\_full = angle\_output;

select\_cos\_mem = 1'b1;

select\_positive = 1'b1;

end

3'b001: begin //45 - 90

angle\_mem\_full = 12'h400 - angle\_output;

select\_cos\_mem = 1'b0;

select\_positive = 1'b1;

end

3'b010: begin //90 - 135

angle\_mem\_full = angle\_output[9:0] - 12'h400;

select\_cos\_mem = 1'b0;

select\_positive = 1'b0;

end

3'b011: begin //135 - 180

angle\_mem\_full = 12'h800 - angle\_output;

select\_cos\_mem = 1'b1;

select\_positive = 1'b0;

end

3'b100: begin //180 - 225

angle\_mem\_full = angle\_output - 12'h800;

select\_cos\_mem = 1'b1;

select\_positive = 1'b0;

end

3'b101: begin //225 - 270

angle\_mem\_full = 12'hC00 - angle\_output;

select\_cos\_mem = 1'b0;

select\_positive = 1'b0;

end

3'b110: begin //270 - 315

angle\_mem\_full = angle\_output - 12'hC00;

select\_cos\_mem = 1'b0;

select\_positive = 1'b1;

end

3'b111: begin //315 - 360

angle\_mem\_full = 13'h1000 - angle\_output;

select\_cos\_mem = 1'b1;

select\_positive = 1'b1;

end

endcase

//exception (when need to return +1.0)

angle\_mem = angle\_mem\_full[9:0];

except = (angle\_mem == 10'b00\_0000\_0000);

except = except || (angle\_mem == 10'b00\_0000\_0001);

except = except || (angle\_mem == 10'b00\_0000\_0010);

except = except || (angle\_mem == 10'b00\_0000\_0011);

except = except || (angle\_mem == 10'b00\_0000\_0100);

except = except || (angle\_mem == 10'b00\_0000\_0101);

//except only work for cos bank near angle 0

except = except & select\_cos\_mem;

//read memory

if (select\_cos\_mem == 1'b1) begin

mem\_val = cos\_mem[angle\_mem];

end else begin

mem\_val = sin\_mem[angle\_mem];

end

//make output

if (select\_positive == 1'b1) begin

result = {mem\_val[14], mem\_val[14] | except, mem\_val[13:0]};

end else begin

result = -{mem\_val[14], mem\_val[14] | except, mem\_val[13:0]};

end

end

endmodule

module compl(

input [11:0] angle,

input start,

input clk,

input reset,

output reg [15:0] r,

output reg [15:0] i

);

parameter IDLE = 2'b00;

parameter COS = 2'b01;

parameter SIN = 2'b10;

reg [1:0] mode, mode\_c;

reg [11:0] angle\_mem, angle\_r;

reg [15:0] r\_c, i\_c;

wire [15:0] cos\_val;

reg cos\_en, start\_r;

initial begin

mode = IDLE;

mode\_c = IDLE;

angle\_mem = 12'b0000\_0000\_0000;

// angle\_r = 12'b0000\_0000\_0000;

r\_c = 16'b0000\_0000\_0000\_0000;

i\_c = 16'b0000\_0000\_0000\_0000;

cos\_en = 1'b0;

// start\_r = 1'b0;

end

cos cos\_mem (.angle (angle\_r), .cos\_en(cos\_en), .result(cos\_val));

//State Machine

always @(angle\_r or start\_r or mode) begin

mode\_c = mode;

case(mode)

IDLE: begin

if (start\_r == 1'b1) begin

mode\_c = COS;

cos\_en = mode\_c[0];

angle\_mem = angle\_r;

end

end

COS: begin

r\_c = cos\_val;

mode\_c = SIN;

cos\_en = mode\_c[0];

end

SIN: begin

i\_c = cos\_val;

mode\_c = IDLE;

end

default: begin

mode\_c = IDLE;

end

endcase

end

//output FFlop

always @(posedge clk or posedge reset) begin

if (reset == 1'b1) begin

r <= #1 16'b0000\_0000\_0000\_0000;

i <= #1 16'b0000\_0000\_0000\_0000;

mode <= #1 IDLE;

angle\_r <= #1 12'b0000\_0000\_0000;

start\_r <= #1 1'b0;

end else begin

r <= #1 r\_c;

i <= #1 i\_c;

mode <= #1 mode\_c;

angle\_r <= #1 angle;

start\_r <= #1 start;

end

end

endmodule

### Testbench:

`timescale 1ns/10ps

module tbench();

reg [11:0] angle;

integer file;

wire [15:0] comp\_r;

wire [15:0] comp\_i;

reg clk, start, rst;

integer count = 0;

compl C1 (

.angle (angle),

.start (start),

.clk (clk),

.reset (rst),

.r (comp\_r),

.i (comp\_i)

);

initial begin

$recordfile("mult\_test");

$recordvars(tbench);

file = $fopen("complex\_result.m", "w");

$fwrite(file, "output = [\n");

angle = 12'b0000\_0000\_0000;

clk = 1'b0;

start = 1'b0;

rst = 1'b1;

#25;

angle = 12'b0000\_0000\_0000;

rst = 1'b0;

start = 1'b1;

count = 3;

end

//clock

always begin

#10;

clk = ~clk;

end

//tests

always @(posedge clk) begin

#2;

if (rst == 1'b0) begin

start = 1'b0;

if (count != 0) begin

count = count - 1;

end else begin

//write result to file

$fwrite(file, "%d %d %d;\n", angle, comp\_r, comp\_i);

//update angle or exit

if (angle == 12'b111111111111) begin

$fwrite(file, "];\n");

$fclose(file);

$finish;

end else begin

angle = angle + 1;

start = 1'b1;

count = 3;

end

end

end

end

endmodule

### Area results:

Clock 1ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:46:21 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 166

Number of cells: 110

Number of combinational cells: 86

Number of sequential cells: 24

Number of macros/black boxes: 0

Number of buf/inv: 12

Number of references: 16

Combinational area: 105.070000

Buf/Inv area: 6.384000

Noncombinational area: 114.380004

Macro/Black Box area: 0.000000

Net Interconnect area: undefined (Wire load has zero net area)

Total cell area: 219.450003

Total area: undefined

1

Clock 4ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:47:34 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 166

Number of cells: 110

Number of combinational cells: 86

Number of sequential cells: 24

Number of macros/black boxes: 0

Number of buf/inv: 12

Number of references: 16

Combinational area: 105.070000

Buf/Inv area: 6.384000

Noncombinational area: 114.380004

Macro/Black Box area: 0.000000

Net Interconnect area: undefined (Wire load has zero net area)

Total cell area: 219.450003

Total area: undefined

1

Clock 20ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:48:52 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 166

Number of cells: 110

Number of combinational cells: 86

Number of sequential cells: 24

Number of macros/black boxes: 0

Number of buf/inv: 12

Number of references: 16

Combinational area: 105.070000

Buf/Inv area: 6.384000

Noncombinational area: 114.380004

Macro/Black Box area: 0.000000

Net Interconnect area: undefined (Wire load has zero net area)

Total cell area: 219.450003

Total area: undefined

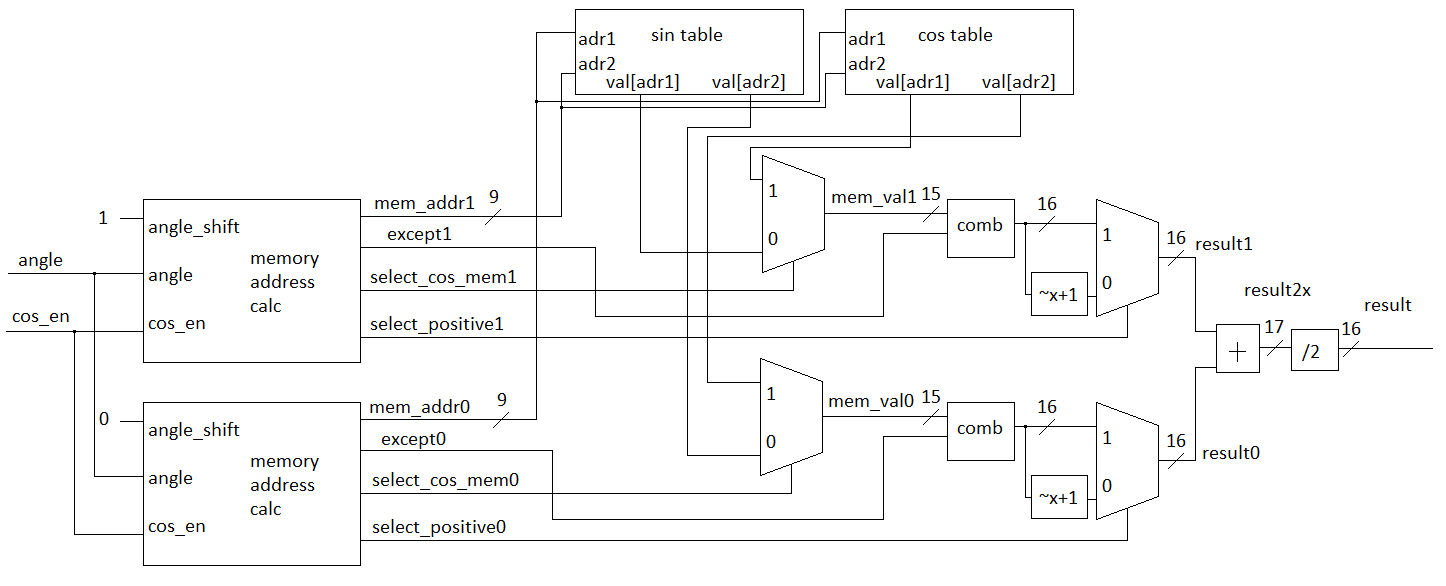
1

## Part 3

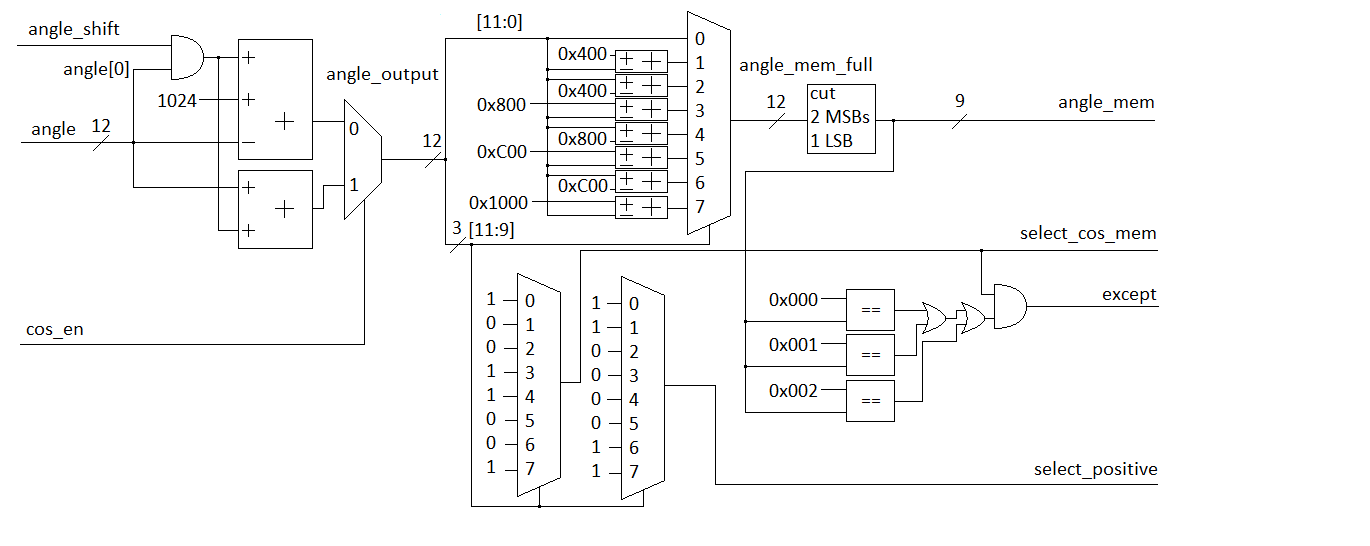
|  |  |
| --- | --- |
| Clock period | Total cell area |
| 4ns | 342.342004 |
| 1ns | 342.342004 |
| 20ns | 342.342004 |

Top –level diagram is the same as in part 1 and 2.

Cos/sin module:



Memory address module:



Energy\_diff / Energy\_data0 = 10\*log(0.002413/4096.016469) = -62.298dB

Difff.m output:

max(data0-data1) = +0.001554 +0.001554i = +0.00155412 +0.00155412i

min(data0-data1) = -0.001554 -0.001554i = -0.00155412 -0.00155412i

max(data0/data1) = -Inf -Infi

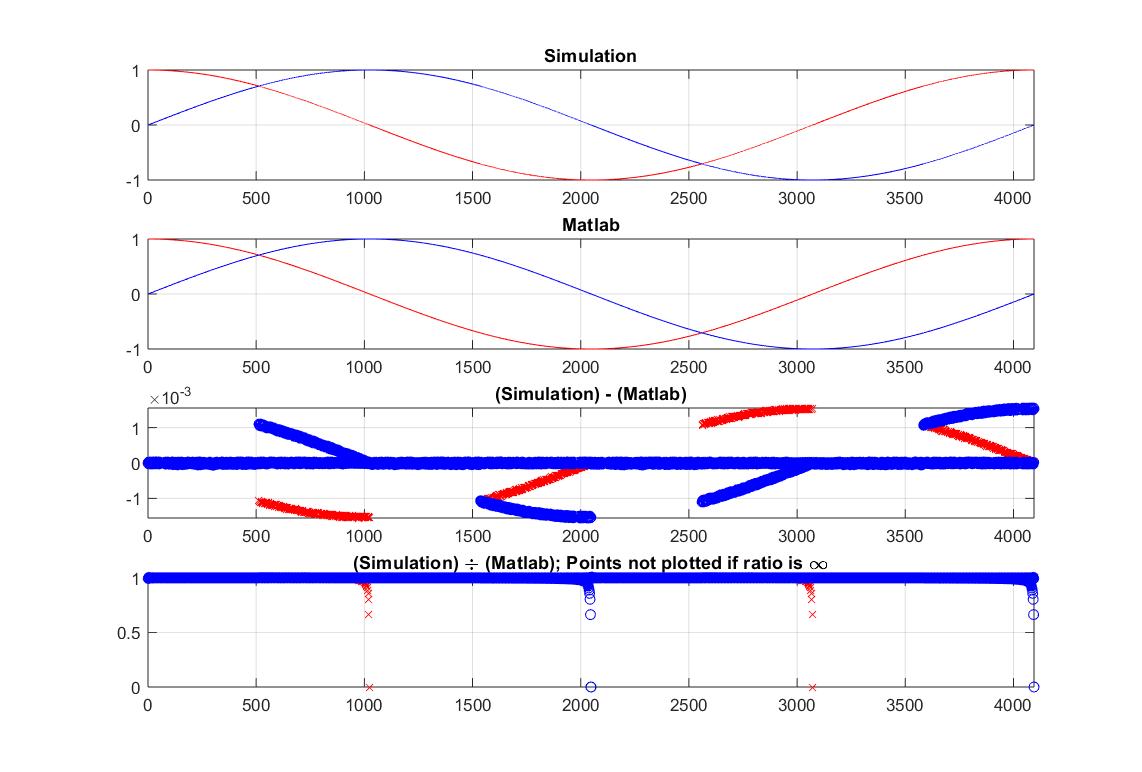
min(data0/data1) = +Inf +Infi

approx separated mean(data0/data1) = +0.997796+ +0.997796i

Energy\_data0 = 4096.016469

Energy\_diff = 0.002413

Energy\_data0/Energy\_diff = 1697518.136491 = 62.298144dB



### Code:

/\*

Top level for complex number generator

\*/

//cos function lookup table

//full precision and [0 .. 45) degrees

`timescale 1ns/10ps

module addr\_selector(

input [11:0] angle,

input angle\_shift,

input cos\_en,

output reg [8:0] mem\_address,

output reg do\_except,

output reg select\_cos\_mem,

output reg select\_positive

);

//logic variables

reg [11:0] angle\_output, angle\_mem\_full;

always @(angle or cos\_en) begin

//cos/sin selection for output

if (cos\_en == 1'b1)

//compute cos(angle)

angle\_output = angle + angle[0]\*angle\_shift;

else

//compute sin(angle) = cos (pi/2 - angle)

angle\_output = 11'b100\_0000\_0000 - angle - angle[0]\*angle\_shift;

//choose cos/sin mem bank

case (angle\_output[11:9])

3'b000: begin //0 - 45

angle\_mem\_full = angle\_output;

select\_cos\_mem = 1'b1;

select\_positive = 1'b1;

end

3'b001: begin //45 - 90

angle\_mem\_full = 12'h400 - angle\_output;

select\_cos\_mem = 1'b0;

select\_positive = 1'b1;

end

3'b010: begin //90 - 135

angle\_mem\_full = angle\_output[9:0] - 12'h400;

select\_cos\_mem = 1'b0;

select\_positive = 1'b0;

end

3'b011: begin //135 - 180

angle\_mem\_full = 12'h800 - angle\_output;

select\_cos\_mem = 1'b1;

select\_positive = 1'b0;

end

3'b100: begin //180 - 225

angle\_mem\_full = angle\_output - 12'h800;

select\_cos\_mem = 1'b1;

select\_positive = 1'b0;

end

3'b101: begin //225 - 270

angle\_mem\_full = 12'hC00 - angle\_output;

select\_cos\_mem = 1'b0;

select\_positive = 1'b0;

end

3'b110: begin //270 - 315

angle\_mem\_full = angle\_output - 12'hC00;

select\_cos\_mem = 1'b0;

select\_positive = 1'b1;

end

3'b111: begin //315 - 360

angle\_mem\_full = 13'h1000 - angle\_output;

select\_cos\_mem = 1'b1;

select\_positive = 1'b1;

end

endcase

//exception (when need to return +1.0)

mem\_address = angle\_mem\_full[9:1];

do\_except = (mem\_address == 10'b00\_0000\_0000);

do\_except = do\_except || (mem\_address == 10'b00\_0000\_0001);

do\_except = do\_except || (mem\_address == 10'b00\_0000\_0010);

//except only work for cos bank near angle 0

do\_except = do\_except & select\_cos\_mem;

end

endmodule

//////////////////////////////////////////////////////////////////

module cos(

input cos\_en,

input [11:0] angle,

output reg [15:0] result

);

reg [15:0] result0, result1;

reg [16:0] result2x;

reg [14:0] cos\_mem [256:0];

reg [14:0] sin\_mem [256:0];

reg [14:0] mem\_val0, mem\_val1;

wire [8:0] mem\_adr0, mem\_adr1;

wire select\_cos\_mem0, select\_cos\_mem1, select\_positive0, select\_positive1, except0, except1;

initial begin

//defaults

result = 16'b0000\_0000\_0000\_0000;

mem\_val0 = 15'b000\_0000\_0000\_0000;

mem\_val1 = 15'b000\_0000\_0000\_0000;

//load values to memory;

cos\_mem[9'b000000000] = 15'b000000000000000; sin\_mem[9'b000000000] = 15'b000000000000000;

cos\_mem[9'b000000001] = 15'b000000000000000; sin\_mem[9'b000000001] = 15'b000000000110010;

cos\_mem[9'b000000010] = 15'b000000000000000; sin\_mem[9'b000000010] = 15'b000000001100101;

cos\_mem[9'b000000011] = 15'b011111111111111; sin\_mem[9'b000000011] = 15'b000000010010111;

cos\_mem[9'b000000100] = 15'b011111111111111; sin\_mem[9'b000000100] = 15'b000000011001001;

cos\_mem[9'b000000101] = 15'b011111111111110; sin\_mem[9'b000000101] = 15'b000000011111011;

cos\_mem[9'b000000110] = 15'b011111111111101; sin\_mem[9'b000000110] = 15'b000000100101110;

cos\_mem[9'b000000111] = 15'b011111111111100; sin\_mem[9'b000000111] = 15'b000000101100000;

cos\_mem[9'b000001000] = 15'b011111111111011; sin\_mem[9'b000001000] = 15'b000000110010010;

cos\_mem[9'b000001001] = 15'b011111111111010; sin\_mem[9'b000001001] = 15'b000000111000100;

cos\_mem[9'b000001010] = 15'b011111111111000; sin\_mem[9'b000001010] = 15'b000000111110111;

cos\_mem[9'b000001011] = 15'b011111111110111; sin\_mem[9'b000001011] = 15'b000001000101001;

cos\_mem[9'b000001100] = 15'b011111111110101; sin\_mem[9'b000001100] = 15'b000001001011011;

cos\_mem[9'b000001101] = 15'b011111111110011; sin\_mem[9'b000001101] = 15'b000001010001101;

cos\_mem[9'b000001110] = 15'b011111111110001; sin\_mem[9'b000001110] = 15'b000001011000000;

//<Many lines removed>

cos\_mem[9'b011110010] = 15'b010111100101000; sin\_mem[9'b011110010] = 15'b010101101000101;

cos\_mem[9'b011110011] = 15'b010111100000110; sin\_mem[9'b011110011] = 15'b010101101101010;

cos\_mem[9'b011110100] = 15'b010111011100100; sin\_mem[9'b011110100] = 15'b010101110001111;

cos\_mem[9'b011110101] = 15'b010111011000010; sin\_mem[9'b011110101] = 15'b010101110110100;

cos\_mem[9'b011110110] = 15'b010111010011111; sin\_mem[9'b011110110] = 15'b010101111011000;

cos\_mem[9'b011110111] = 15'b010111001111101; sin\_mem[9'b011110111] = 15'b010101111111101;

cos\_mem[9'b011111000] = 15'b010111001011010; sin\_mem[9'b011111000] = 15'b010110000100001;

cos\_mem[9'b011111001] = 15'b010111000110111; sin\_mem[9'b011111001] = 15'b010110001000110;

cos\_mem[9'b011111010] = 15'b010111000010101; sin\_mem[9'b011111010] = 15'b010110001101010;

cos\_mem[9'b011111011] = 15'b010110111110010; sin\_mem[9'b011111011] = 15'b010110010001110;

cos\_mem[9'b011111100] = 15'b010110111001111; sin\_mem[9'b011111100] = 15'b010110010110010;

cos\_mem[9'b011111101] = 15'b010110110101011; sin\_mem[9'b011111101] = 15'b010110011010110;

cos\_mem[9'b011111110] = 15'b010110110001000; sin\_mem[9'b011111110] = 15'b010110011111010;

cos\_mem[9'b011111111] = 15'b010110101100101; sin\_mem[9'b011111111] = 15'b010110100011110;

cos\_mem[9'b100000000] = 15'b010110101000001; sin\_mem[9'b100000000] = 15'b010110101000001;

end

//address calculation for bottom value

addr\_selector ADS0 (

.angle (angle),

.angle\_shift (1'b0),

.cos\_en (cos\_en),

.mem\_address (mem\_adr0),

.do\_except (except0),

.select\_cos\_mem (select\_cos\_mem0),

.select\_positive (select\_positive0)

);

//address calculation for upper value

addr\_selector ADS1 (

.angle (angle),

.angle\_shift (1'b1),

.cos\_en (cos\_en),

.mem\_address (mem\_adr1),

.do\_except (except1),

.select\_cos\_mem (select\_cos\_mem1),

.select\_positive (select\_positive1)

);

//calculate upper value

always @(mem\_adr1 or mem\_adr1 or select\_cos\_mem1 or select\_positive1) begin

//read memory

if (select\_cos\_mem1 == 1'b1) begin

mem\_val1 = cos\_mem[mem\_adr1];

end else begin

mem\_val1 = sin\_mem[mem\_adr1];

end

if (select\_positive1 == 1'b1) begin

result1 = {mem\_val1[14], mem\_val1[14] | except1, mem\_val1[13:0]};

end else begin

result1 = -{mem\_val1[14], mem\_val1[14] | except1, mem\_val1[13:0]};

end

end

//calculate bottom value

always @(mem\_adr0 or mem\_adr0 or select\_cos\_mem0 or select\_positive0) begin

//read memory

if (select\_cos\_mem0 == 1'b1) begin

mem\_val0 = cos\_mem[mem\_adr0];

end else begin

mem\_val0 = sin\_mem[mem\_adr0];

end

if (select\_positive0 == 1'b1) begin

result0 = {mem\_val0[14], mem\_val0[14] | except0, mem\_val0[13:0]};

end else begin

result0 = -{mem\_val0[14], mem\_val0[14] | except0, mem\_val0[13:0]};

end

end

//write output

always @(result1 or result0) begin

result2x = {result1[15], result1} + {result0[15], result0};

result = result2x[16:1]; //devide by 2

end

endmodule

module compl(

input [11:0] angle,

input start,

input clk,

input reset,

output reg [15:0] r,

output reg [15:0] i

);

parameter IDLE = 2'b00;

parameter COS = 2'b01;

parameter SIN = 2'b10;

reg [1:0] mode, mode\_c;

reg [11:0] angle\_mem, angle\_r;

reg [15:0] r\_c, i\_c;

wire [15:0] cos\_val;

reg cos\_en, start\_r;

initial begin

mode = IDLE;

mode\_c = IDLE;

angle\_mem = 12'b0000\_0000\_0000;

// angle\_r = 12'b0000\_0000\_0000;

r\_c = 16'b0000\_0000\_0000\_0000;

i\_c = 16'b0000\_0000\_0000\_0000;

cos\_en = 1'b0;

// start\_r = 1'b0;

end

cos cos\_mem (.angle (angle\_r), .cos\_en(cos\_en), .result(cos\_val));

//State Machine

always @(angle\_r or start\_r or mode) begin

mode\_c = mode;

case(mode)

IDLE: begin

if (start\_r == 1'b1) begin

mode\_c = COS;

cos\_en = mode\_c[0];

angle\_mem = angle\_r;

end

end

COS: begin

r\_c = cos\_val;

mode\_c = SIN;

cos\_en = mode\_c[0];

end

SIN: begin

i\_c = cos\_val;

mode\_c = IDLE;

end

default: begin

mode\_c = IDLE;

end

endcase

end

//output FFlop

always @(posedge clk or posedge reset) begin

if (reset == 1'b1) begin

r <= #1 16'b0000\_0000\_0000\_0000;

i <= #1 16'b0000\_0000\_0000\_0000;

mode <= #1 IDLE;

angle\_r <= #1 12'b0000\_0000\_0000;

start\_r <= #1 1'b0;

end else begin

r <= #1 r\_c;

i <= #1 i\_c;

mode <= #1 mode\_c;

angle\_r <= #1 angle;

start\_r <= #1 start;

end

end

endmodule

### Testbench:

`timescale 1ns/10ps

module tbench();

reg [11:0] angle;

integer file;

wire [15:0] comp\_r;

wire [15:0] comp\_i;

reg clk, start, rst;

integer count = 0;

compl C1 (

.angle (angle),

.start (start),

.clk (clk),

.reset (rst),

.r (comp\_r),

.i (comp\_i)

);

initial begin

$recordfile("mult\_test");

$recordvars(tbench);

file = $fopen("complex\_result.m", "w");

$fwrite(file, "output = [\n");

angle = 12'b0000\_0000\_0000;

clk = 1'b0;

start = 1'b0;

rst = 1'b1;

#25;

angle = 12'b0000\_0000\_0000;

rst = 1'b0;

start = 1'b1;

count = 3;

end

//clock

always begin

#10;

clk = ~clk;

end

//tests

always @(posedge clk) begin

#2;

if (rst == 1'b0) begin

start = 1'b0;

if (count != 0) begin

count = count - 1;

end else begin

//write result to file

$fwrite(file, "%d %d %d;\n", angle, comp\_r, comp\_i);

//update angle or exit

if (angle == 12'b111111111111) begin

$fwrite(file, "];\n");

$fclose(file);

$finish;

end else begin

angle = angle + 1;

start = 1'b1;

count = 3;

end

end

end

end

endmodule

### Area results:

Clock 1ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:51:18 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 249

Number of cells: 195

Number of combinational cells: 167

Number of sequential cells: 28

Number of macros/black boxes: 0

Number of buf/inv: 23

Number of references: 17

Combinational area: 212.001999

Buf/Inv area: 12.502000

Noncombinational area: 130.340004

Macro/Black Box area: 0.000000

Net Interconnect area: undefined (Wire load has zero net area)

Total cell area: 342.342004

Total area: undefined

1

Clock 4ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:53:01 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 249

Number of cells: 195

Number of combinational cells: 167

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Number of buf/inv: 23

Number of references: 17

Combinational area: 212.001999

Buf/Inv area: 12.502000

Noncombinational area: 130.340004

Macro/Black Box area: 0.000000

Net Interconnect area: undefined (Wire load has zero net area)

Total cell area: 342.342004

Total area: undefined

1

Clock 20ns:

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Report : area

Design : compl

Version: J-2014.09-SP2

Date : Mon Mar 12 22:54:08 2018

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Information: Updating design information... (UID-85)

Library(s) Used:

NangateOpenCellLibrary (File: /software/Synopsys/DesignCompiler/EEC281/lib/nangate45/NangateOpenCellLibrary.db)

Number of ports: 47

Number of nets: 249

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Total area: undefined

1