FFT Project

Mohamed Adel Abdelrahem Ahmed

mhmdadel344@gmail.com

01129411207

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Eng. Omar Fahmy

Introduction – Design Phases

- System modeling using MATLAB.
- RTL design.
- RTL verification.
- ASIC implementation using (OpenLane).
- We will go through the System modeling and RTL design , simple RTL verification , start of the ASIC.

Overview of FFT

- It's "fast fourier transform" an algorithm that computes the discrete fourier transform "DFT" of a sequence , or its inverse.
- A fourier transform converts a signal from its original domain to a representation in the frequency domain and vice versa.
- FFT manages to reduce the complexity of computing the DFT from O(n^2) to O(nxlog n) where n is the data size.
- we will implement 8-point FFT.
- Architecture used is iterative (one butterfly reused across time steps) , and in-place (reuse the same memory for updates).
- The input/outputs is bit-reversed
- Radix-2 mean the input size N must be of power 2.
- the algorithm recursively splits the signal into even and odd indexed parts ,compute FFT of both , and combines using twiddle factors.

Overview of butterfly

- We can replace the 2-point DFT with a butterfly

Figure 4-3. FFT implementation of an 8-point DFT as two 4-point DFTs and four 2-point DFTs.

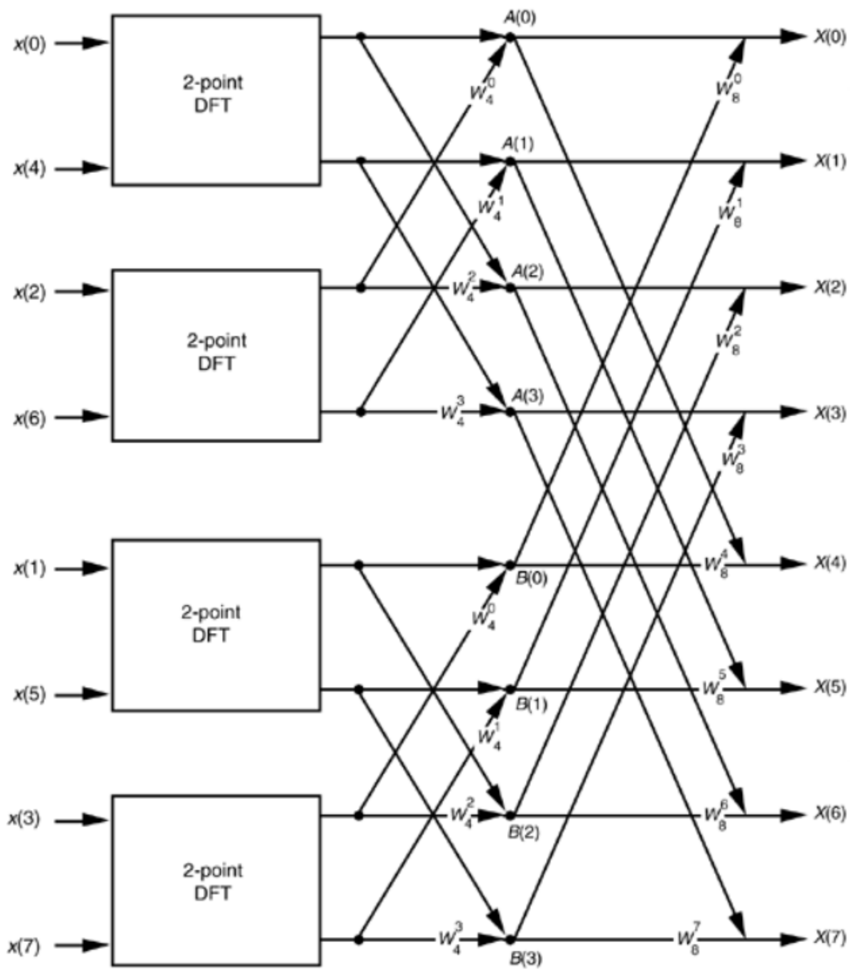
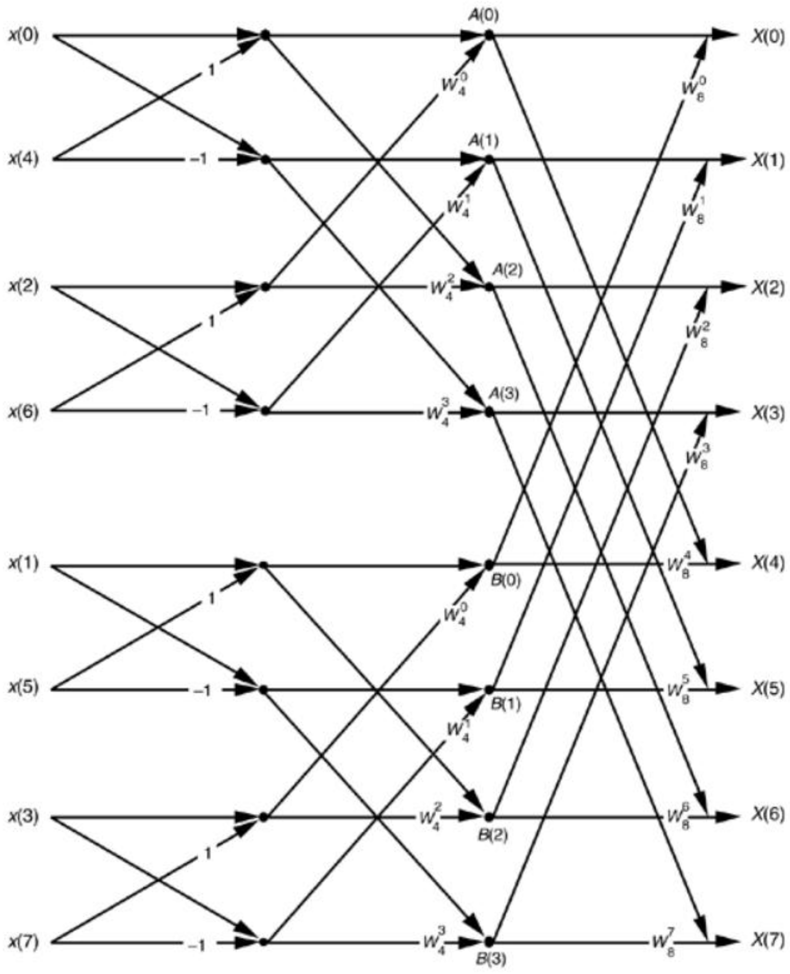


Figure 4-5. Full decimation-in-time FFT implementation of an 8-point DFT.



Overview of Twiddle Factor

- $W_N^m = e^{-j2pi(m/N)}$

$$X(m) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi nm/N}.$$

$$X(m) = \sum_{n=0}^{(N/2)-1} x(2n) e^{-j2\pi(2n)m/N} + \sum_{n=0}^{(N/2)-1} x(2n+1) e^{-j2\pi(2n+1)m/N}.$$

$$X(m) = \sum_{n=0}^{(N/2)-1} x(2n) e^{-j2\pi(2n)m/N} + e^{-j2\pi m/N} \sum_{n=0}^{(N/2)-1} x(2n+1) e^{-j2\pi(2n)m/N}.$$

$$X(m) = \sum_{n=0}^{(N/2)-1} x(2n) W_N^{2nm} + W_N^m \sum_{n=0}^{(N/2)-1} x(2n+1) W_N^{2nm}.$$

[DERIVATION OF THE RADIX-2 FFT ALGORITHM | Chapter Four. The Fast Fourier Transform]

Here, we consider about the property of the twiddle factor. The twiddle factor has the periodic property as be shown in equation (2.2)

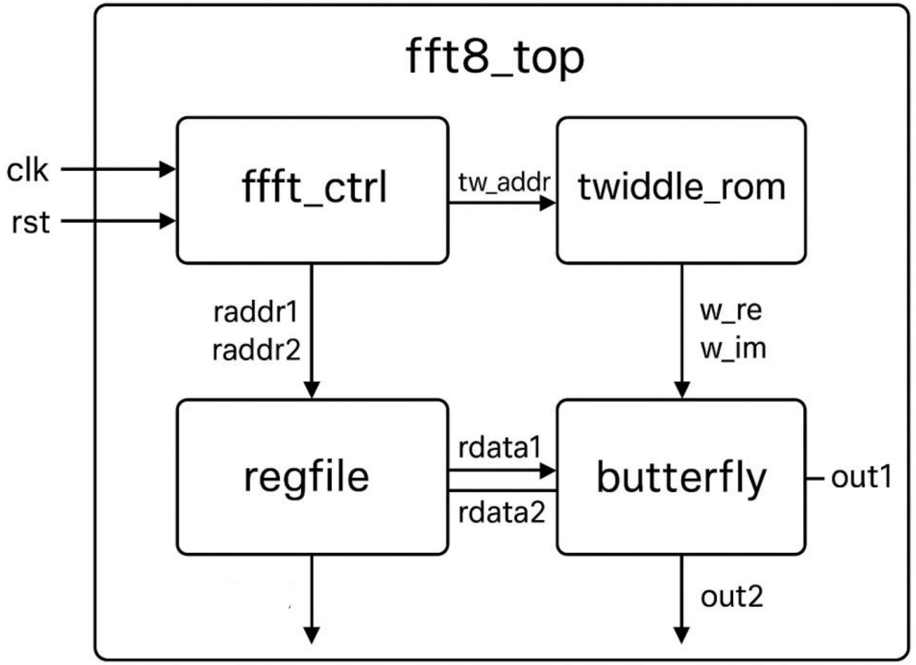
$$\left(\begin{array}{l} W_N{}^{k+N} = W_N{}^k \\ W_N{}^{k+\frac{N}{2}} = -W_N{}^k \end{array} \right)$$

Block diagram

- N=8 , W=12 , F=8
- fft_ctrl is FSM that control the flow of the design
- butterfly block of the 2-point DFT

-twiddle_rom contain twiddles factor values

-regfile have the mem that store the input and rewrite the out values

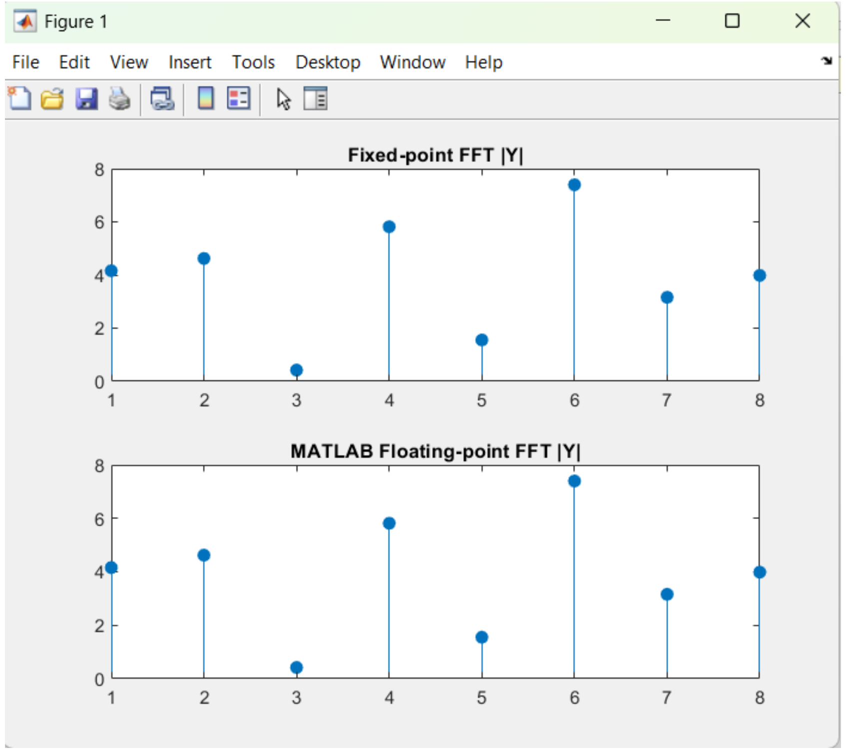


MATLAB

```
>> test_fft_prepared_fixpt
Max real: 1.438, Min real: -2.944
Max imag: 0.628, Min imag: -0.865
Fixed-point error norm = 2.686e-03
SQNR vs MATLAB FFT = 73.340 dB
Fixed-point output min: 0.422, max: 7.396
Fixed-point input samples:
  Columns 1 through 6
   1.0938 - 0.7695i   1.1094 + 0.3711i  -0.8633 - 0.2266i   0.0781 + 1.1172i  -1.2148 - 1.0898i  -1.1133 + 0.0312i
  Columns 7 through 8
  -0.0078 + 0.5508i   1.5312 + 1.1016i

          DataTypeMode: Fixed-point: binary point scaling
            Signedness: Signed
            WordLength: 12
        FractionLength: 8
Stored integers (hex):
X[1] re=118 im=F3B
X[2] re=11C im=05F
X[3] re=F23 im=FC6
X[4] re=014 im=11E
X[5] re=EC9 im=EE9
X[6] re=EE3 im=008
X[7] re=FFE im=08D
X[8] re=188 im=11A
Fixed-point FFT output samples:
  Columns 1 through 6
   0.6133 + 1.0859i   4.3828 + 0.8594i  -1.0664 - 0.5703i   0.7383 - 1.3086i  -2.5977 - 4.1562i  -1.3203 + 1.4922i
  Columns 7 through 8
   2.5664 - 3.7969i   5.4336 + 0.2383i

          DataTypeMode: Fixed-point: binary point scaling
            Signedness: Signed
            WordLength: 12
        FractionLength: 8
Stored integers (hex):
Y[1] re=09D im=116
Y[2] re=462 im=0DC
Y[3] re=EEF im=F6E
Y[4] re=0BD im=EB1
Y[5] re=D67 im=BD8
Y[6] re=EAE im=17E
Y[7] re=291 im=C34
Y[8] re=56F im=03D
```



Input/output files

• They will be sent to the testbench

input_data.mem | expected_output.mem

File Edit View

```
118
F3B
11C
05F
F23
FC6
014
11E
EC9
EE9
EE3
008
FFE
08D
188
11A
```

input_data.mem | expected_output.mem

File Edit View

```
09D
116
462
0DC
EEF
F6E
0BD
EB1
D67
BD8
EAE
17E
291
C34
56F
03D
```

Questasim

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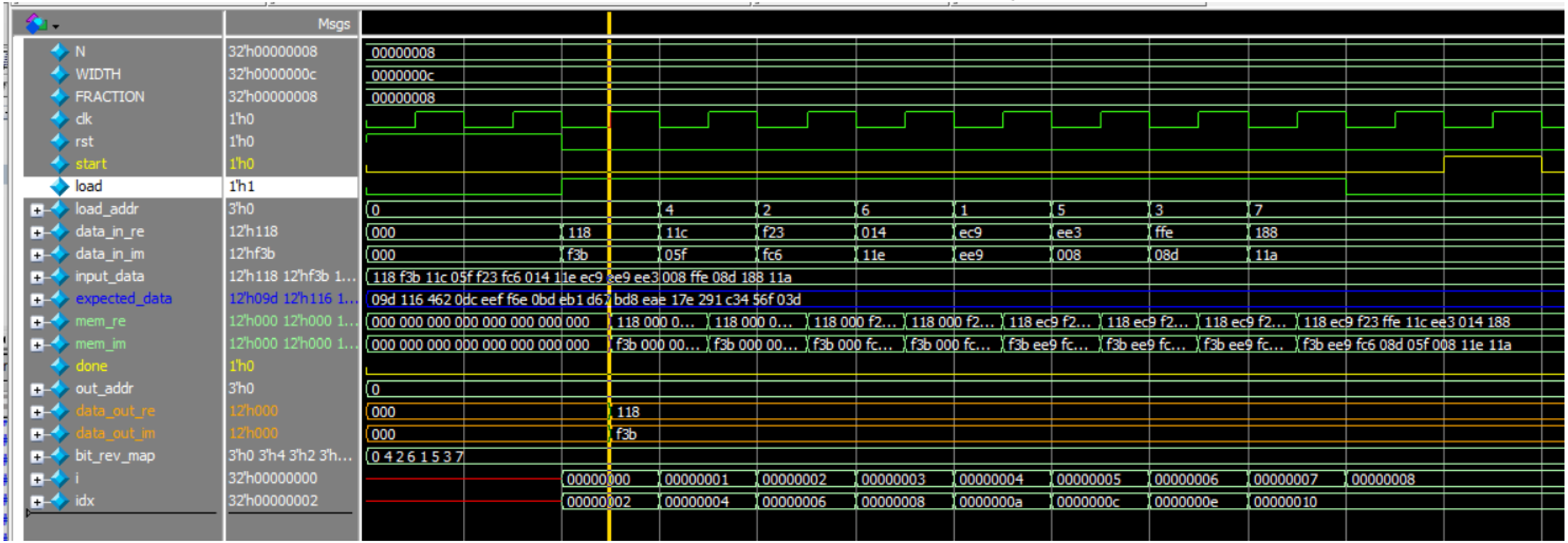
- For this result easily divide it by 256 to be in form of Q4.8 just like matlab
- Wave form loading inputs

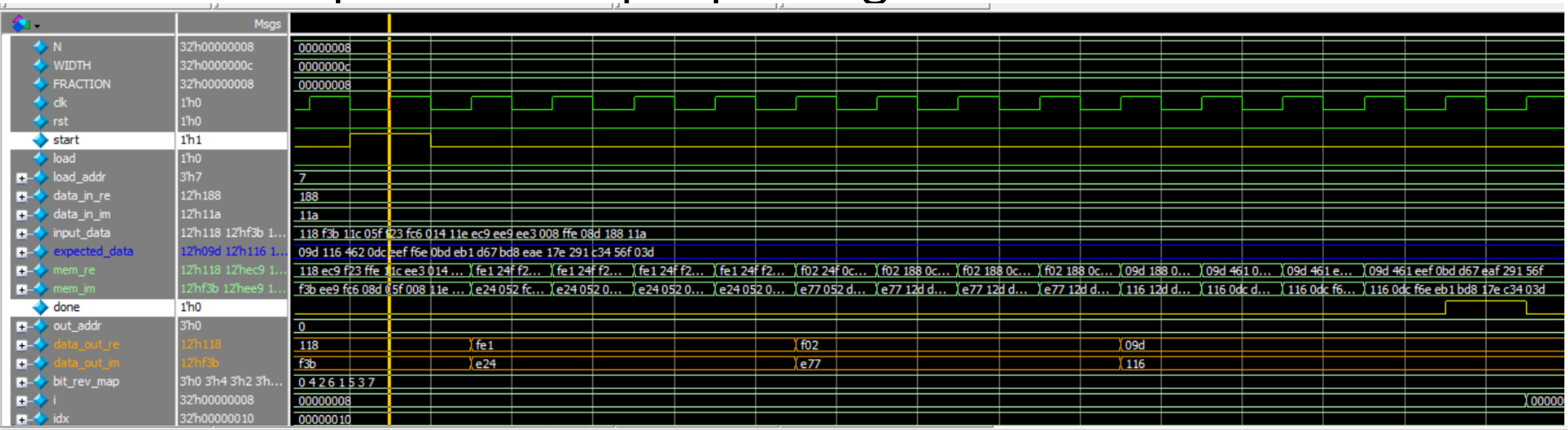
It took 8 cycles

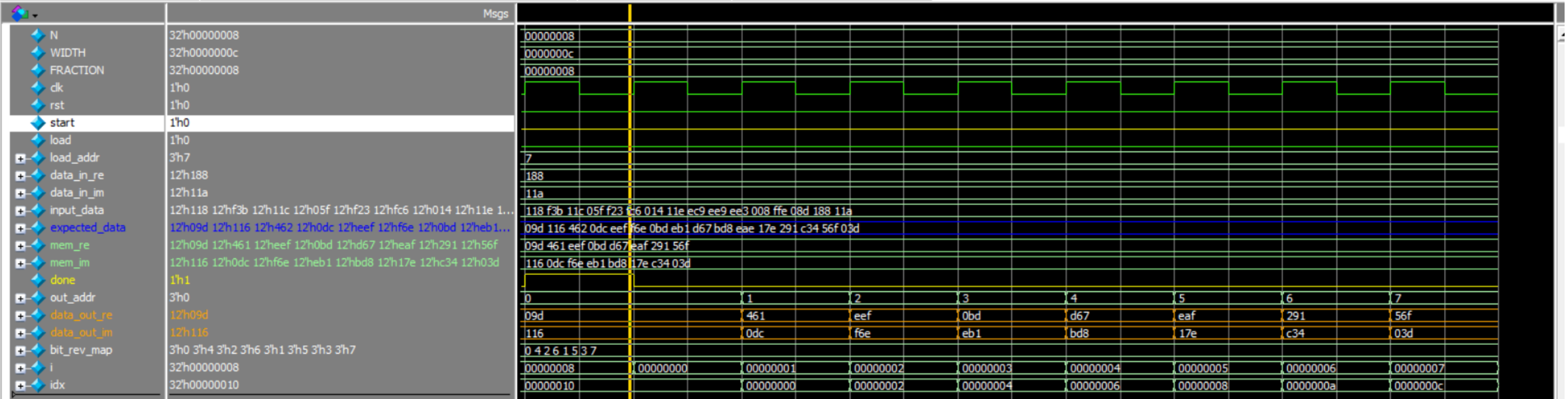
```
# === FFT Output Comparison ===
# Y[0] DUT: 157 + j278    | Expected: 157 + j278
#    -> MATCH
# Y[1] DUT: 1121 + j220    | Expected: 1122 + j220
#    -> MISMATCH
# Y[2] DUT: -273 + j-146    | Expected: -273 + j-146
#    -> MATCH
# Y[3] DUT: 189 + j-335    | Expected: 189 + j-335
#    -> MATCH
# Y[4] DUT: -665 + j-1064    | Expected: -665 + j-1064
#    -> MATCH
# Y[5] DUT: -337 + j382    | Expected: -338 + j382
#    -> MISMATCH
# Y[6] DUT: 657 + j-972    | Expected: 657 + j-972
#    -> MATCH
# Y[7] DUT: 1391 + j61    | Expected: 1391 + j61
#    -> MATCH
# ** Note: $stop    : fft_testbench.v(222)
#    Time: 335 ns  Iteration: 0  Instance: /fft8_tb
# Break in Module fft8_tb at fft_testbench.v line 222
```



Questasim

- Calculation phase & Output printing





Latency from the previous slide

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- Latency = 9 cycles from all inputs loaded to the first output sample.
- And = 12 cycles from all inputs loaded "start=1" to "done=1" all outputs calculated.
- If we need it from the first input sample before start=1 the we will add 8 cycles since the inputs is loaded in 8-cycles.

Notes on SQNR

- For higher sqnr it is more better
- For my model in matlab the avg sqnr approx. =70dB for single run
- But when I tried 10 or 50 or 100 it drop down to 38,40dB and 70 is perfect and between 30…60dB is accepted in most DSP blocks , but below 30dB is recognized easily.

For N output samples:

$$\mathrm{SQNR} = 10\log_{10}\left(\frac{\sum_{n=0}^{N-1}|y_{\text{float}}(n)|^2}{\sum_{n=0}^{N-1}|y_{\text{float}}(n) - y_{\text{fixed}}(n)|^2}\right)\ \mathrm{dB}$$

- **Numerator** → total signal power of the ideal output.
- **Denominator** → total error power caused by fixed-point quantization.

Coverage Report

```
=====================================================================================
=== Instance: /fft8_tb/dut/ctrl
=== Design Unit: work.fft8_ctrl
=====================================================================================
Branch Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Branches                        14        13         1    92.85%

================================Branch Details================================
-----------------------------------CASE Branch----------------------------------
    46                                        17     Count coming in to CASE
    47             1                           4
    56             1                          12
    69             1                           1
                                          ***0***    All False Count
Branch totals: 3 hits of 4 branches = 75.00%

Condition Coverage:
    Enabled Coverage              Bins   Covered    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Conditions                       3         3         0   100.00%

Statement Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Statements                      32        32         0   100.00%

Toggle Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Toggles                        182        58       124    31.86%
```

```
=== Design Unit: work.twiddle_rom
=====================================================================================
Branch Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Branches                         5         4         1    80.00%
  File twiddle_rom.v
------------------------------------CASE Branch------------------------------------
    22                                         9     Count coming in to CASE
    23             1                           4
    27             1                           1
    31             1                           3
    35             1                           1
    39             1                     ***0***
Branch totals: 4 hits of 5 branches = 80.00%

Statement Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Statements                      11         9         2    81.81%

Toggle Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Toggles                         52        44         8    84.61%
```

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```
=== Design Unit: work.regfile_fft
=====================================================================================
Branch Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Branches                         8         8         0   100.00%

Statement Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Statements                      18        18         0   100.00%

Toggle Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Toggles                        398       330        68    82.91%
```

```
=== Design Unit: work.butterfly
=====================================================================================
Statement Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Statements                       8         8         0   100.00%

Toggle Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Toggles                        384       364        20    94.79%
```

```
=== Instance: /fft8_tb/dut
=== Design Unit: work.fft8_top
=====================================================================================
Toggle Coverage:
    Enabled Coverage              Bins      Hits    Misses  Coverage
    ----------------              ----      ----    ------  --------
    Toggles                        390       378        12    96.92%
```

```
Total Coverage By Instance (filtered view): 91.75%
```