VLSI DPS HW#4

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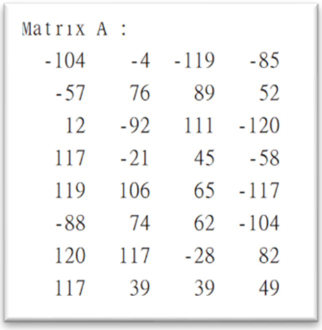
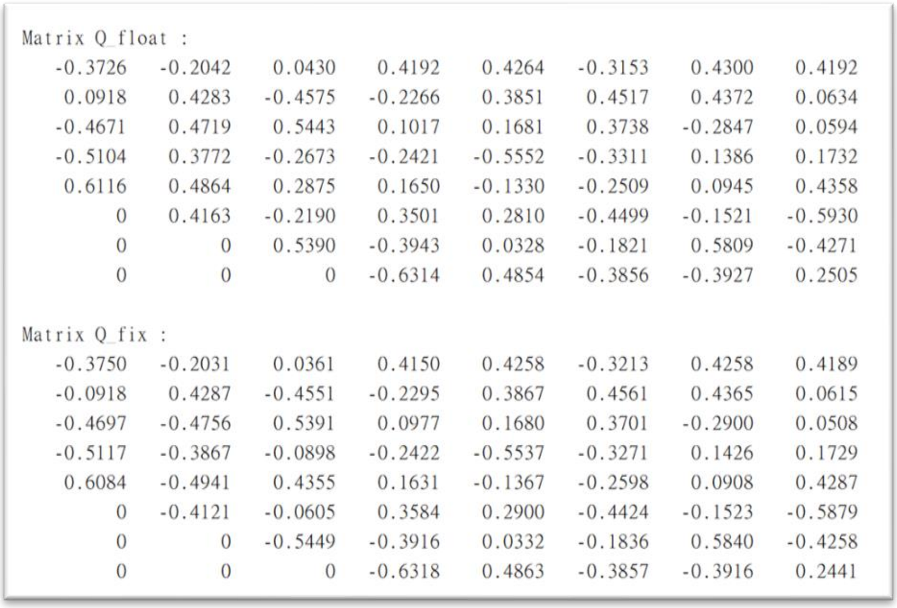
1. Calculate the Frobenius Distance

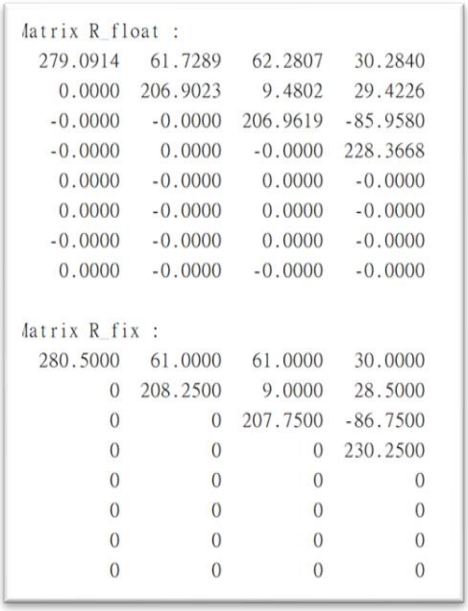


```
Matrix A :
  -104    -4  -119   -85
   -57    76    89    52
    12   -92   111  -120
   117   -21    45   -58
   119   106    65  -117
   -88    74    62  -104
   120   117   -28    82
   117    39    39    49
```

● Generate a random matrix A

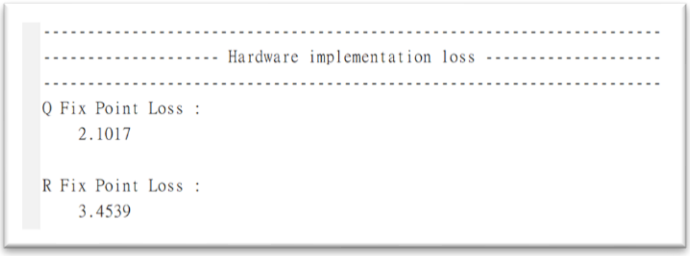


```
Matrix Q_float :
   -0.3726   -0.2042    0.0430    0.4192    0.4264   -0.3153    0.4300    0.4192
    0.0918    0.4283   -0.4575   -0.2266    0.3851    0.4517    0.4372    0.0634
   -0.4671    0.4719    0.5443    0.1017    0.1681    0.3738   -0.2847    0.0594
   -0.5104    0.3772   -0.2673   -0.2421   -0.5552   -0.3311    0.1386    0.1732
    0.6116    0.4864    0.2875    0.1650   -0.1330   -0.2509    0.0945    0.4358
         0    0.4163   -0.2190    0.3501    0.2810   -0.4499   -0.1521   -0.5930
         0         0    0.5390   -0.3943    0.0328   -0.1821    0.5809   -0.4271
         0         0         0   -0.6314    0.4854   -0.3856   -0.3927    0.2505

Matrix Q_fix :
   -0.3750   -0.2031    0.0361    0.4150    0.4258   -0.3213    0.4258    0.4189
   -0.0918    0.4287   -0.4551   -0.2295    0.3867    0.4561    0.4365    0.0615
   -0.4697   -0.4756    0.5391    0.0977    0.1680    0.3701   -0.2900    0.0508
   -0.5117   -0.3867   -0.0898   -0.2422   -0.5537   -0.3271    0.1426    0.1729
    0.6084   -0.4941    0.4355    0.1631   -0.1367   -0.2598    0.0908    0.4287
         0   -0.4121   -0.0605    0.3584    0.2900   -0.4424   -0.1523   -0.5879
         0         0   -0.5449   -0.3916    0.0332   -0.1836    0.5840   -0.4258
         0         0         0   -0.6318    0.4863   -0.3857   -0.3916    0.2441
```



```
latrix R_float :
  279.0914   61.7289   62.2807   30.2840
    0.0000  206.9023    9.4802   29.4226
   -0.0000   -0.0000  206.9619  -85.9580
   -0.0000    0.0000   -0.0000  228.3668
    0.0000   -0.0000    0.0000   -0.0000
    0.0000   -0.0000    0.0000   -0.0000
   -0.0000   -0.0000    0.0000   -0.0000
    0.0000   -0.0000   -0.0000   -0.0000

latrix R_fix :
  280.5000   61.0000   61.0000   30.0000
         0  208.2500    9.0000   28.5000
         0         0  207.7500  -86.7500
         0         0         0  230.2500
         0         0         0         0
         0         0         0         0
         0         0         0         0
         0         0         0         0
```

- Q_float and R_float are generated from Q*[A|I] =[R|Q]
- Q_fix and R_fix are generated from Cordic given’s rotation
- The Frobenius Distance (Euclidean Norm) is sqrt(trace((float-fix)*(float-fix)'))

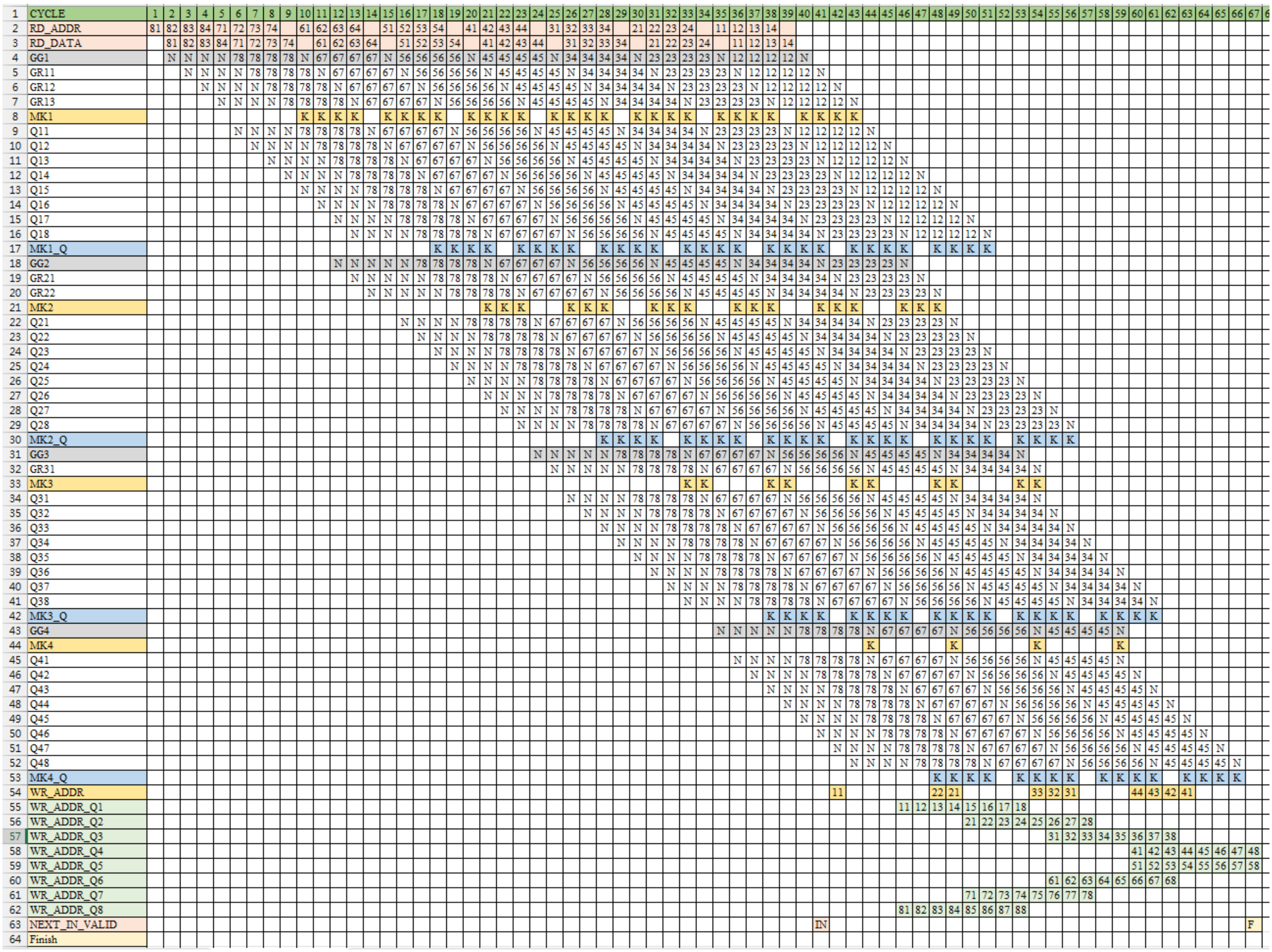


```
-----------------------------------------------------------------
------------------ Hardware implementation loss ------------------
-----------------------------------------------------------------
Q Fix Point Loss :
    2.1017

R Fix Point Loss :
    3.4539
```

- Fix-point precision

Data	Sign bit	Integer part	Fraction part	Length
A (input)	1	7	0	8
Q (output)	1	1	10	12
R (output)	1	9	2	12
K (parameter)	1	0	9	10

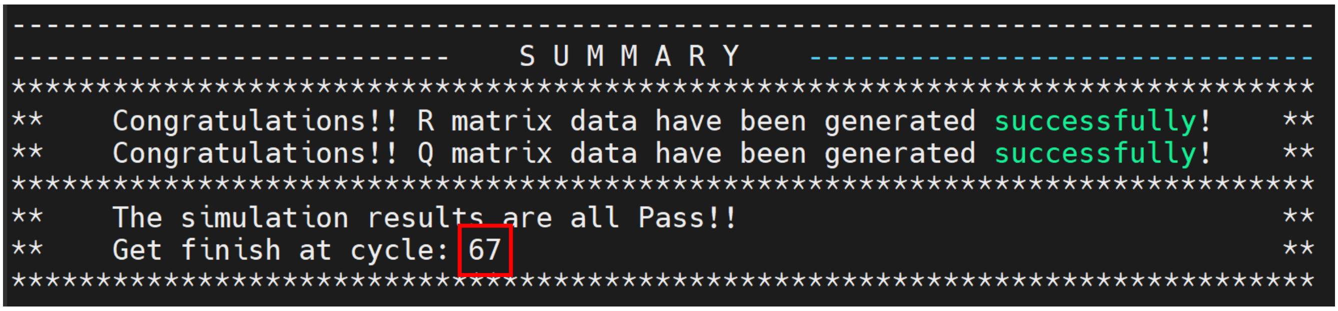
2. Timing diagram



1	CYCLE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
2	RD_ADDR	81	82	83	84	71	72	73	74		61	62	63	64		51	52	53	54		41	42	43	44		31	32	33	34		21	22	23	24		11	12	13	14																													
3	RD_DATA		81	82	83	84	71	72	73	74		61	62	63	64		51	52	53	54		41	42	43	44		31	32	33	34		21	22	23	24		11	12	13	14																												
4	GG1		N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																											
5	GR11			N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																										
6	GR12				N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																									
7	GR13					N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																								
8	MK1										K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K																									
9	Q11						N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																							
10	Q12							N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																						
11	Q13								N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																					
12	Q14									N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																				
13	Q15										N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																			
14	Q16											N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																		
15	Q17												N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																	
16	Q18													N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N																
17	MK1_Q																		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K																
18	GG2												N	N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N																					
19	GR21													N	N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N																				
20	GR22														N	N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N																			
21	MK2																					K	K	K			K	K	K			K	K	K			K	K	K			K	K	K			K	K	K																			
22	Q21																N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N																		
23	Q22																	N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N																	
24	Q23																		N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N																
25	Q24																			N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N															
26	Q25																				N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N														
27	Q26																					N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N													
28	Q27																						N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N												
29	Q28																							N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N											
30	MK2_Q																												K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K											
31	GG3																								N	N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N														
32	GR31																									N	N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N													
33	MK3																																	K	K				K	K				K	K				K	K				K	K													
34	Q31																										N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N													
35	Q32																											N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N												
36	Q33																												N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N											
37	Q34																													N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N										
38	Q35																														N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N									
39	Q36																															N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N								
40	Q37																																N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N							
41	Q38																																	N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N						
42	MK3_Q																																						K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K						
43	GG4																																			N	N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N								
44	MK4																																												K					K					K					K								
45	Q41																																				N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N								
46	Q42																																					N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N							
47	Q43																																						N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N						
48	Q44																																							N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N					
49	Q45																																								N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N				
50	Q46																																									N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N			
51	Q47																																										N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N		
52	Q48																																											N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	
53	MK4_Q																																																K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K	
54	WR_ADDR																																										11						22	21					33	32	31				44	43	42	41				
55	WR_ADDR_Q1																																														11	12	13	14	15	16	17	18														
56	WR_ADDR_Q2																																																		21	22	23	24	25	26	27	28										
57	WR_ADDR_Q3																																																							31	32	33	34	35	36	37	38					
58	WR_ADDR_Q4																																																												41	42	43	44	45	46	47	48
59	WR_ADDR_Q5																																																												51	52	53	54	55	56	57	58
60	WR_ADDR_Q6																																																							61	62	63	64	65	66	67	68					
61	WR_ADDR_Q7																																																		71	72	73	74	75	76	77	78										
62	WR_ADDR_Q8																																														81	82	83	84	85	86	87	88														
63	NEXT_IN_VALID																																									IN																										F
64	Finish																																																																			

- N : No Operation(idle)
- K : Multiplied by K
- 78 78 78 78 N : Perform rotation on 7th and 8th row
- 11 12 13 14 15 16 17 18: The matrix index of data write back to tb

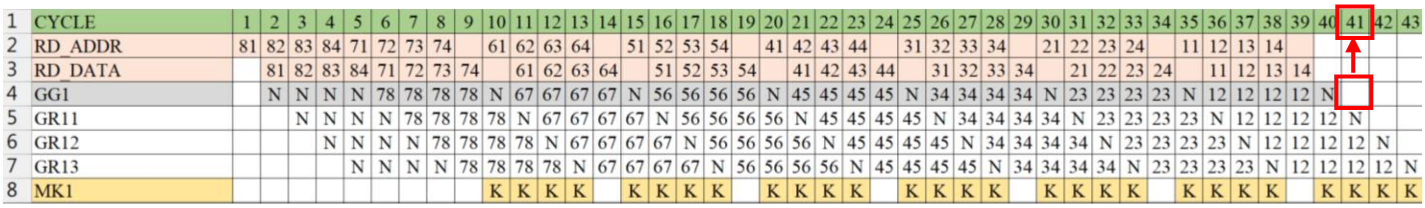
3. Clock cycles needed to complete one QR factorization



```
-----------------------------------------------------------------------------
-------------------------    S U M M A R Y    ------------------------------
****************************************************************************
**     Congratulations!! R matrix data have been generated successfully!    **
**     Congratulations!! Q matrix data have been generated successfully!    **
****************************************************************************
**     The simulation results are all Pass!!                                **
**     Get finish at cycle: 67                                              **
****************************************************************************
```

67 cycles

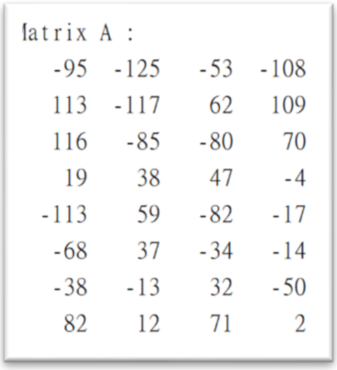
4. The initiation interval of two successive QR factorizations



1	CYCLE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
2	RD_ADDR	81	82	83	84	71	72	73	74		61	62	63	64		51	52	53	54		41	42	43	44		31	32	33	34		21	22	23	24		11	12	13	14					
3	RD_DATA		81	82	83	84	71	72	73	74		61	62	63	64		51	52	53	54		41	42	43	44		31	32	33	34		21	22	23	24		11	12	13	14				
4	GG1		N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N			
5	GR11			N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N		
6	GR12				N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N	
7	GR13					N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N
8	MK1										K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K

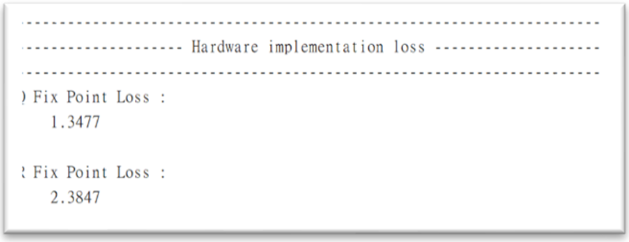
When GG1 performs all vectoring over, the next input is valid.
The initiation interval is 41 cycles.

● Matlab result



```
latrix A :
     -95  -125   -53  -108
     113  -117    62   109
     116   -85   -80    70
      19    38    47    -4
    -113    59   -82   -17
     -68    37   -34   -14
     -38   -13    32   -50
      82    12    71     2
```

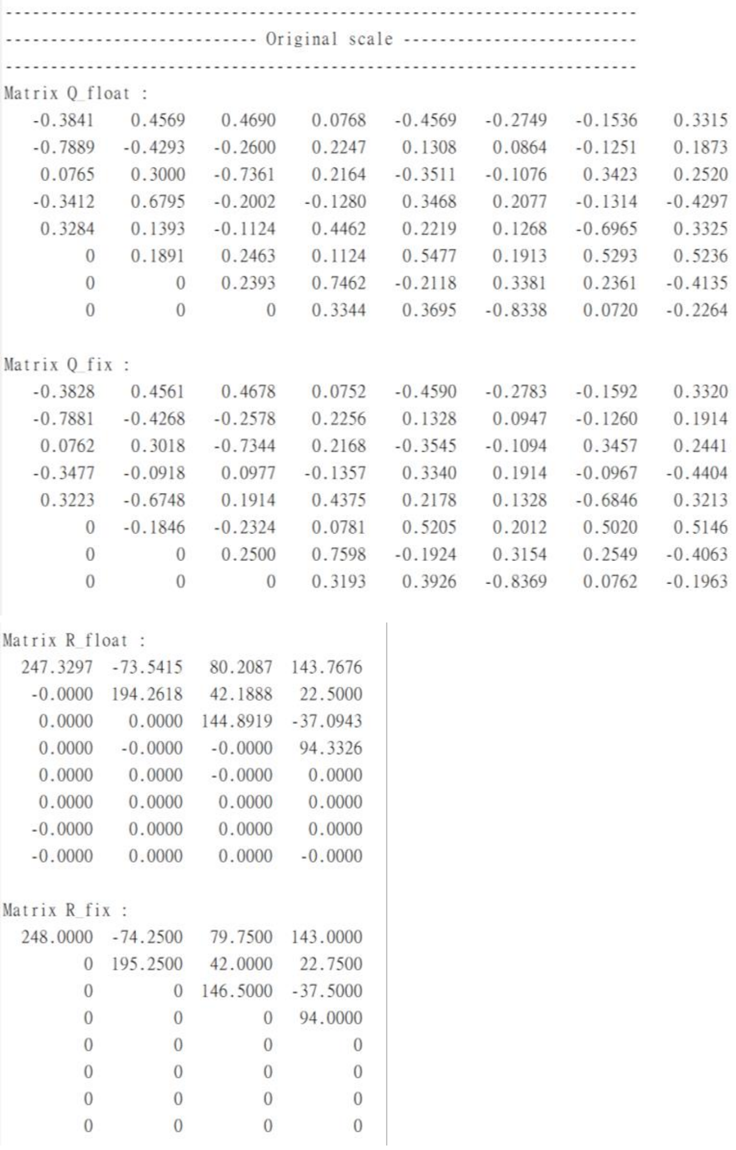
- ● Random matrix A
- ● Hardware loss



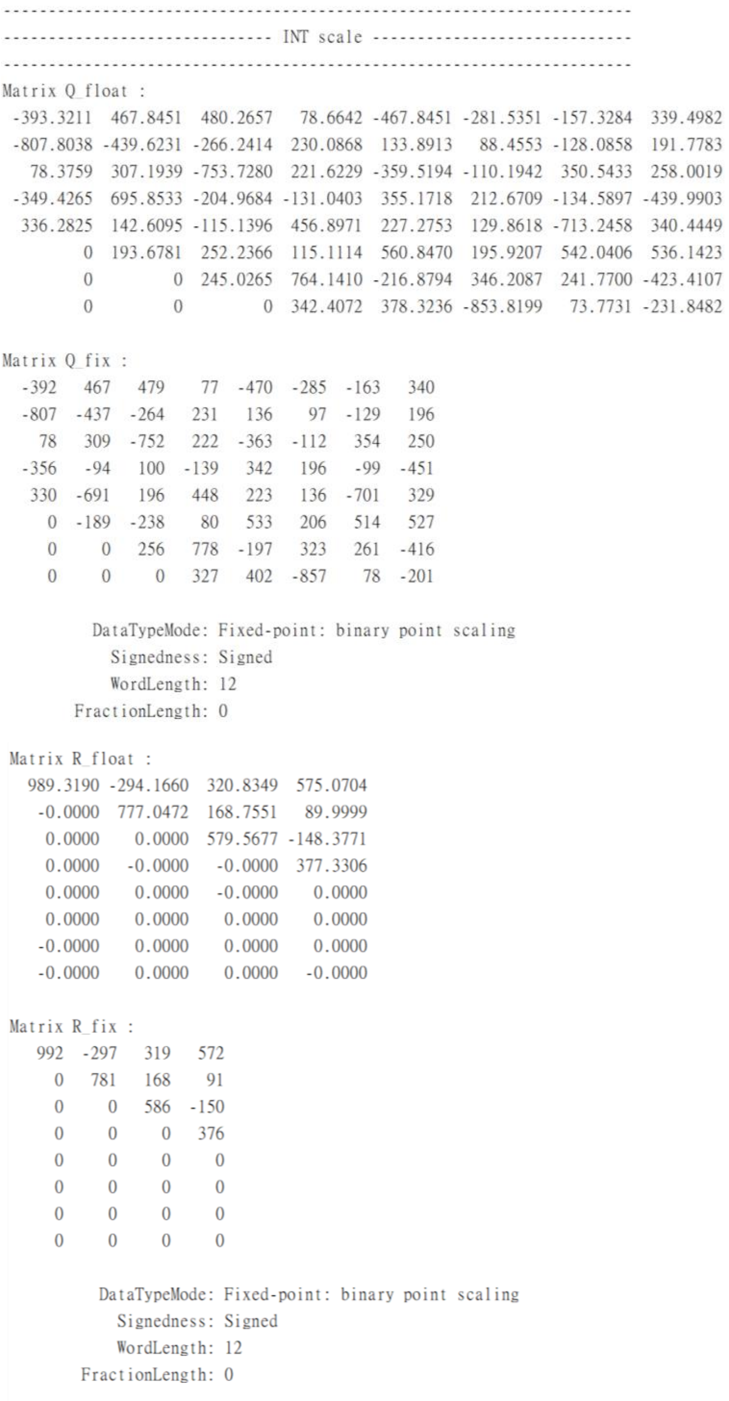
```
----------------------------------------------------------------------
------------------- Hardware implementation loss -------------------
----------------------------------------------------------------------
) Fix Point Loss :
    1.3477

: Fix Point Loss :
    2.3847
```

Actual values

Shift to integer to simulate hardware performance



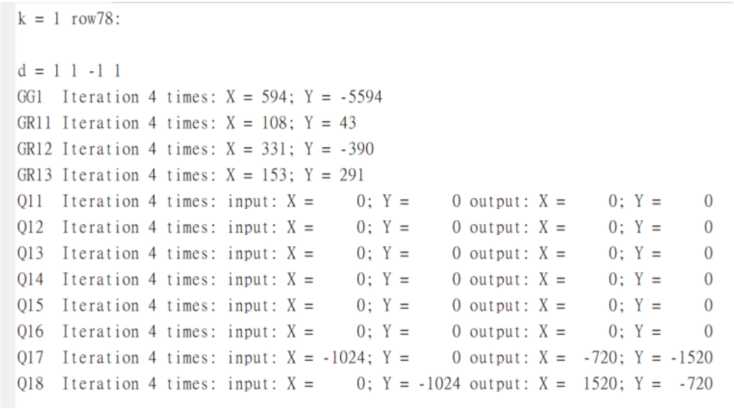
```
-----------------------------------------------------------------------
--------------------------- Original scale -------------------------
-----------------------------------------------------------------------
Matrix Q_float :
   -0.3841    0.4569    0.4690    0.0768   -0.4569   -0.2749   -0.1536    0.3315
   -0.7889   -0.4293   -0.2600    0.2247    0.1308    0.0864   -0.1251    0.1873
    0.0765    0.3000   -0.7361    0.2164   -0.3511   -0.1076    0.3423    0.2520
   -0.3412    0.6795   -0.2002   -0.1280    0.3468    0.2077   -0.1314   -0.4297
    0.3284    0.1393   -0.1124    0.4462    0.2219    0.1268   -0.6965    0.3325
         0    0.1891    0.2463    0.1124    0.5477    0.1913    0.5293    0.5236
         0         0    0.2393    0.7462   -0.2118    0.3381    0.2361   -0.4135
         0         0         0    0.3344    0.3695   -0.8338    0.0720   -0.2264

Matrix Q_fix :
   -0.3828    0.4561    0.4678    0.0752   -0.4590   -0.2783   -0.1592    0.3320
   -0.7881   -0.4268   -0.2578    0.2256    0.1328    0.0947   -0.1260    0.1914
    0.0762    0.3018   -0.7344    0.2168   -0.3545   -0.1094    0.3457    0.2441
   -0.3477   -0.0918    0.0977   -0.1357    0.3340    0.1914   -0.0967   -0.4404
    0.3223   -0.6748    0.1914    0.4375    0.2178    0.1328   -0.6846    0.3213
         0   -0.1846   -0.2324    0.0781    0.5205    0.2012    0.5020    0.5146
         0         0    0.2500    0.7598   -0.1924    0.3154    0.2549   -0.4063
         0         0         0    0.3193    0.3926   -0.8369    0.0762   -0.1963

Matrix R_float :
  247.3297  -73.5415   80.2087  143.7676
   -0.0000  194.2618   42.1888   22.5000
    0.0000    0.0000  144.8919  -37.0943
    0.0000   -0.0000   -0.0000   94.3326
    0.0000    0.0000   -0.0000    0.0000
    0.0000    0.0000    0.0000    0.0000
   -0.0000    0.0000    0.0000    0.0000
   -0.0000    0.0000    0.0000   -0.0000

Matrix R_fix :
  248.0000  -74.2500   79.7500  143.0000
         0  195.2500   42.0000   22.7500
         0         0  146.5000  -37.5000
         0         0         0   94.0000
         0         0         0         0
         0         0         0         0
         0         0         0         0
         0         0         0         0
```



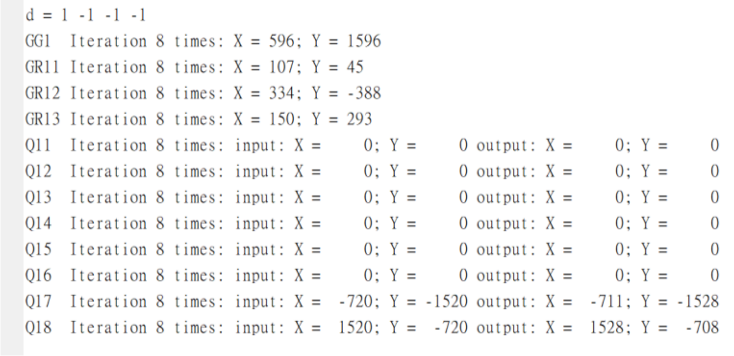
```
-----------------------------------------------------------------------
---------------------------- INT scale ----------------------------
-----------------------------------------------------------------------
Matrix Q_float :
 -393.3211  467.8451  480.2657   78.6642 -467.8451 -281.5351 -157.3284  339.4982
 -807.8038 -439.6231 -266.2414  230.0868  133.8913   88.4553 -128.0858  191.7783
   78.3759  307.1939 -753.7280  221.6229 -359.5194 -110.1942  350.5433  258.0019
 -349.4265  695.8533 -204.9684 -131.0403  355.1718  212.6709 -134.5897 -439.9903
  336.2825  142.6095 -115.1396  456.8971  227.2753  129.8618 -713.2458  340.4449
         0  193.6781  252.2366  115.1114  560.8470  195.9207  542.0406  536.1423
         0         0  245.0265  764.1410 -216.8794  346.2087  241.7700 -423.4107
         0         0         0  342.4072  378.3236 -853.8199   73.7731 -231.8482

Matrix Q_fix :
  -392   467   479    77  -470  -285  -163   340
  -807  -437  -264   231   136    97  -129   196
    78   309  -752   222  -363  -112   354   250
  -356   -94   100  -139   342   196   -99  -451
   330  -691   196   448   223   136  -701   329
     0  -189  -238    80   533   206   514   527
     0     0   256   778  -197   323   261  -416
     0     0     0   327   402  -857    78  -201

          DataTypeMode: Fixed-point: binary point scaling
            Signedness: Signed
            WordLength: 12
        FractionLength: 0

Matrix R_float :
  989.3190 -294.1660  320.8349  575.0704
   -0.0000  777.0472  168.7551   89.9999
    0.0000    0.0000  579.5677 -148.3771
    0.0000   -0.0000   -0.0000  377.3306
    0.0000    0.0000   -0.0000    0.0000
    0.0000    0.0000    0.0000    0.0000
   -0.0000    0.0000    0.0000    0.0000
   -0.0000    0.0000    0.0000   -0.0000

Matrix R_fix :
   992  -297   319   572
     0   781   168    91
     0     0   586  -150
     0     0     0   376
     0     0     0     0
     0     0     0     0
     0     0     0     0
     0     0     0     0

          DataTypeMode: Fixed-point: binary point scaling
            Signedness: Signed
            WordLength: 12
        FractionLength: 0
```

● Matlab result

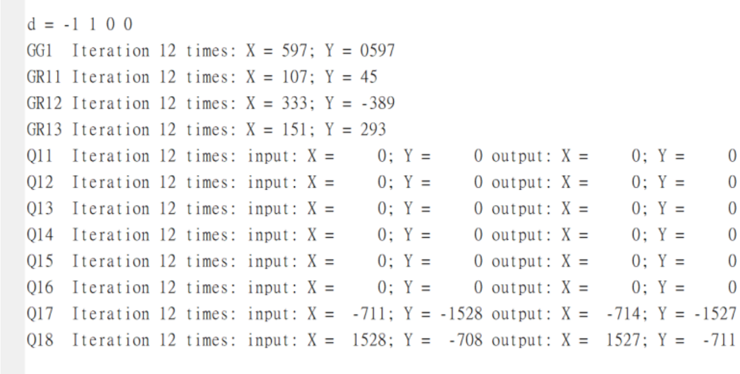
Record the values during iteration, which can be used for debugging in hardware implementation.



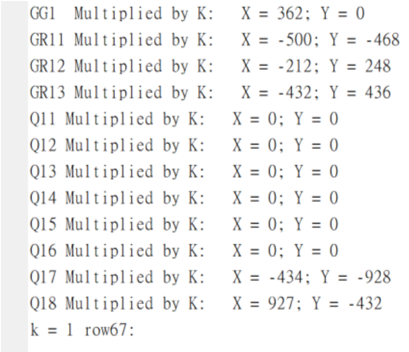
```
k = 1 row78:

d = 1 1 -1 1
GG1  Iteration 4 times: X = 594; Y = -5594
GR11 Iteration 4 times: X = 108; Y = 43
GR12 Iteration 4 times: X = 331; Y = -390
GR13 Iteration 4 times: X = 153; Y = 291
Q11  Iteration 4 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q12  Iteration 4 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q13  Iteration 4 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q14  Iteration 4 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q15  Iteration 4 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q16  Iteration 4 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q17  Iteration 4 times: input: X = -1024; Y =     0 output: X =  -720; Y = -1520
Q18  Iteration 4 times: input: X =     0; Y = -1024 output: X =  1520; Y =  -720
```



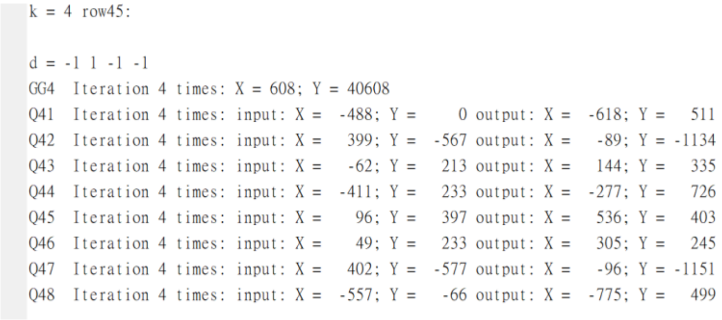
```
d = 1 -1 -1 -1
GG1  Iteration 8 times: X = 596; Y = 1596
GR11 Iteration 8 times: X = 107; Y = 45
GR12 Iteration 8 times: X = 334; Y = -388
GR13 Iteration 8 times: X = 150; Y = 293
Q11  Iteration 8 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q12  Iteration 8 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q13  Iteration 8 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q14  Iteration 8 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q15  Iteration 8 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q16  Iteration 8 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q17  Iteration 8 times: input: X =  -720; Y = -1520 output: X =  -711; Y = -1528
Q18  Iteration 8 times: input: X =  1520; Y =  -720 output: X =  1528; Y =  -708
```



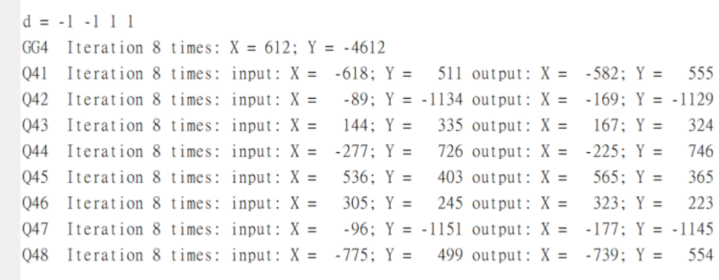
```
d = -1 1 0 0
GG1  Iteration 12 times: X = 597; Y = 0597
GR11 Iteration 12 times: X = 107; Y = 45
GR12 Iteration 12 times: X = 333; Y = -389
GR13 Iteration 12 times: X = 151; Y = 293
Q11  Iteration 12 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q12  Iteration 12 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q13  Iteration 12 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q14  Iteration 12 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q15  Iteration 12 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q16  Iteration 12 times: input: X =     0; Y =     0 output: X =     0; Y =     0
Q17  Iteration 12 times: input: X =  -711; Y = -1528 output: X =  -714; Y = -1527
Q18  Iteration 12 times: input: X =  1528; Y =  -708 output: X =  1527; Y =  -711
```



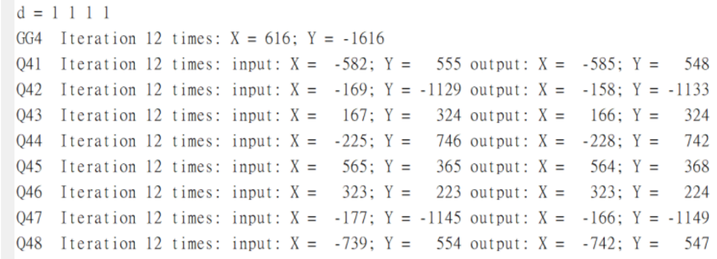
```
GG1  Multiplied by K:   X = 362; Y = 0
GR11 Multiplied by K:   X = -500; Y = -468
GR12 Multiplied by K:   X = -212; Y = 248
GR13 Multiplied by K:   X = -432; Y = 436
Q11 Multiplied by K:   X = 0; Y = 0
Q12 Multiplied by K:   X = 0; Y = 0
Q13 Multiplied by K:   X = 0; Y = 0
Q14 Multiplied by K:   X = 0; Y = 0
Q15 Multiplied by K:   X = 0; Y = 0
Q16 Multiplied by K:   X = 0; Y = 0
Q17 Multiplied by K:   X = -434; Y = -928
Q18 Multiplied by K:   X = 927; Y = -432
k = 1 row67:
```



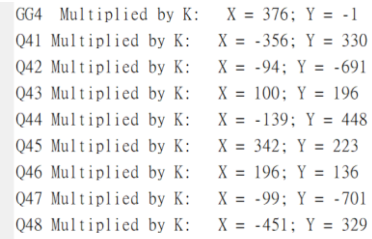
```
k = 4 row45:

d = -1 1 -1 -1
GG4  Iteration 4 times: X = 608; Y = 40608
Q41  Iteration 4 times: input: X =  -488; Y =     0 output: X =  -618; Y =   511
Q42  Iteration 4 times: input: X =   399; Y =  -567 output: X =   -89; Y = -1134
Q43  Iteration 4 times: input: X =   -62; Y =   213 output: X =   144; Y =   335
Q44  Iteration 4 times: input: X =  -411; Y =   233 output: X =  -277; Y =   726
Q45  Iteration 4 times: input: X =    96; Y =   397 output: X =   536; Y =   403
Q46  Iteration 4 times: input: X =    49; Y =   233 output: X =   305; Y =   245
Q47  Iteration 4 times: input: X =   402; Y =  -577 output: X =   -96; Y = -1151
Q48  Iteration 4 times: input: X =  -557; Y =   -66 output: X =  -775; Y =   499
```



```
d = -1 -1 1 1
GG4  Iteration 8 times: X = 612; Y = -4612
Q41  Iteration 8 times: input: X =  -618; Y =   511 output: X =  -582; Y =   555
Q42  Iteration 8 times: input: X =   -89; Y = -1134 output: X =  -169; Y = -1129
Q43  Iteration 8 times: input: X =   144; Y =   335 output: X =   167; Y =   324
Q44  Iteration 8 times: input: X =  -277; Y =   726 output: X =  -225; Y =   746
Q45  Iteration 8 times: input: X =   536; Y =   403 output: X =   565; Y =   365
Q46  Iteration 8 times: input: X =   305; Y =   245 output: X =   323; Y =   223
Q47  Iteration 8 times: input: X =   -96; Y = -1151 output: X =  -177; Y = -1145
Q48  Iteration 8 times: input: X =  -775; Y =   499 output: X =  -739; Y =   554
```



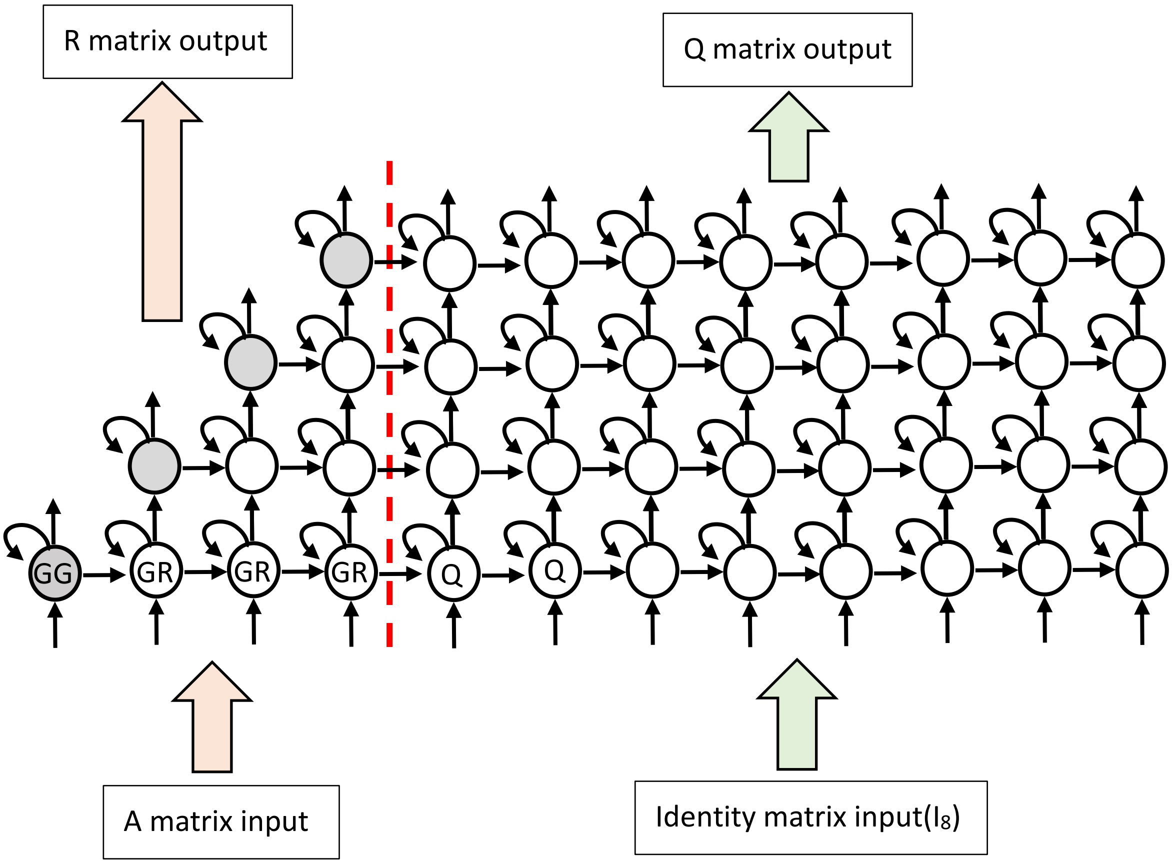
```
d = 1 1 1 1
GG4  Iteration 12 times: X = 616; Y = -1616
Q41  Iteration 12 times: input: X =  -582; Y =   555 output: X =  -585; Y =   548
Q42  Iteration 12 times: input: X =  -169; Y = -1129 output: X =  -158; Y = -1133
Q43  Iteration 12 times: input: X =   167; Y =   324 output: X =   166; Y =   324
Q44  Iteration 12 times: input: X =  -225; Y =   746 output: X =  -228; Y =   742
Q45  Iteration 12 times: input: X =   565; Y =   365 output: X =   564; Y =   368
Q46  Iteration 12 times: input: X =   323; Y =   223 output: X =   323; Y =   224
Q47  Iteration 12 times: input: X =  -177; Y = -1145 output: X =  -166; Y = -1149
Q48  Iteration 12 times: input: X =  -739; Y =   554 output: X =  -742; Y =   547
```

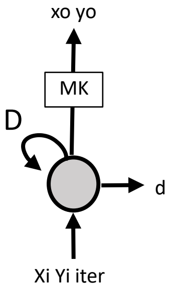


```
GG4  Multiplied by K:   X = 376; Y = -1
Q41 Multiplied by K:   X = -356; Y = 330
Q42 Multiplied by K:   X = -94; Y = -691
Q43 Multiplied by K:   X = 100; Y = 196
Q44 Multiplied by K:   X = -139; Y = 448
Q45 Multiplied by K:   X = 342; Y = 223
Q46 Multiplied by K:   X = 196; Y = 136
Q47 Multiplied by K:   X = -99; Y = -701
Q48 Multiplied by K:   X = -451; Y = 329
```

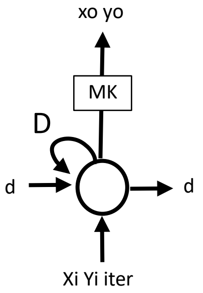
Hardware implementation result

1. Hardware architecture





GG(vectoring mode) : One GG contains 4 micro-rotation modules, when iteration over, it outputs to above and multiplied by K(MK module), the rest of data will be transmitted to the right GR and Q modules.



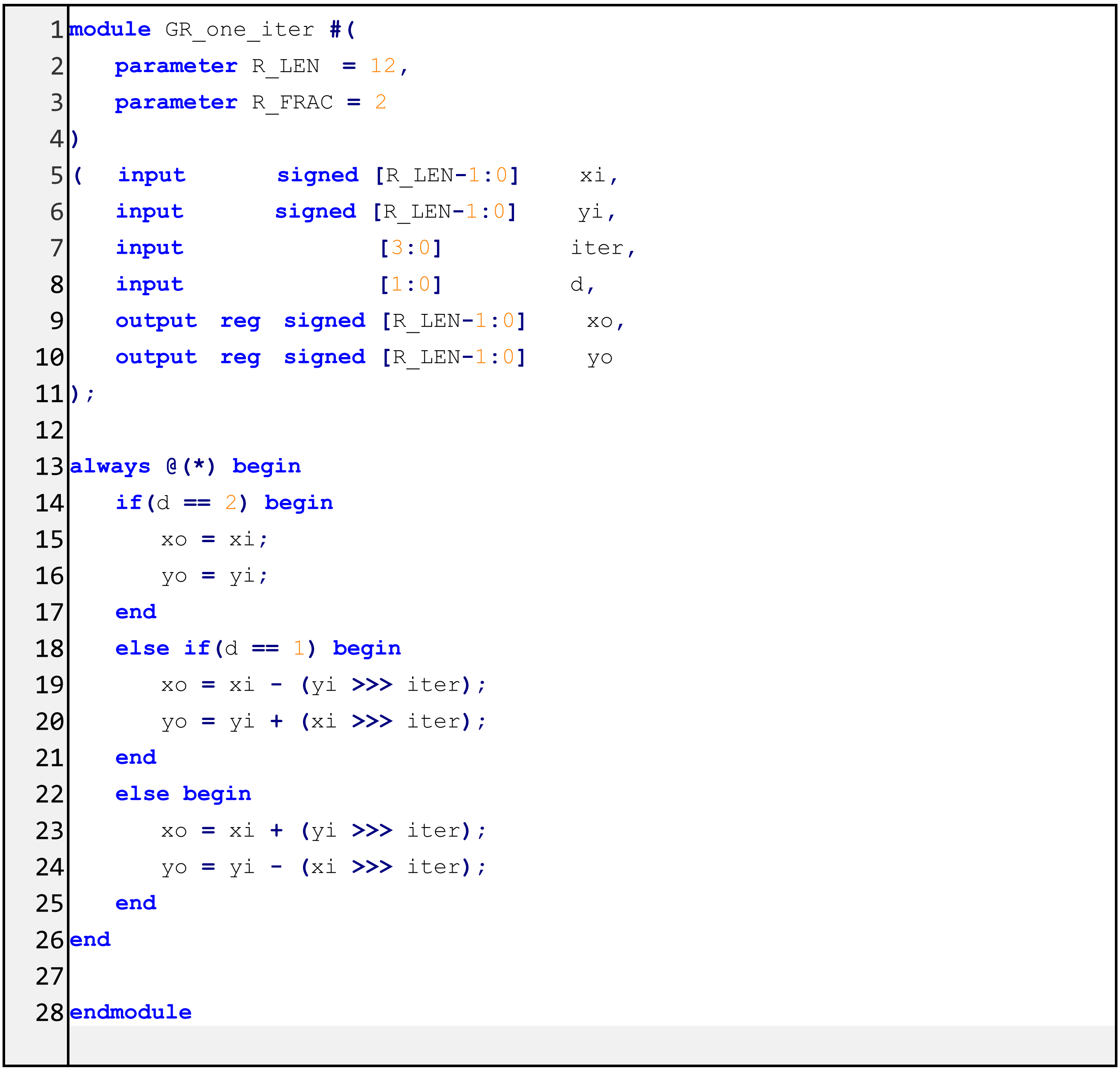
GR(rotation mode) : GR is almost the same module as GG, the only difference is rotation direction d, d will input from the left module(GG or GR).

2. Verilog code (only core part):

a. GG module

```
module GG_one_iter #(
    parameter R_LEN  = 12,
    parameter R_FRAC = 2
)(
    input      signed [R_LEN-1:0]    xi,
    input      signed [R_LEN-1:0]    yi,
    input             [3:0]          iter,
    output            [1:0]          d,
    output  reg signed [R_LEN-1:0]    xo,
    output  reg signed [R_LEN-1:0]    yo
);

assign d = (yi == 0) ? 2 : xi[R_LEN-1] ^ yi[R_LEN-1];

always @(*) begin
    if(d == 2) begin
        xo = xi;
        yo = yi;
    end
    else if(d == 1) begin
        xo = xi - (yi >>> iter);
        yo = yi + (xi >>> iter);
    end
    else begin
        xo = xi + (yi >>> iter);
        yo = yi - (xi >>> iter);
    end
end

endmodule
```

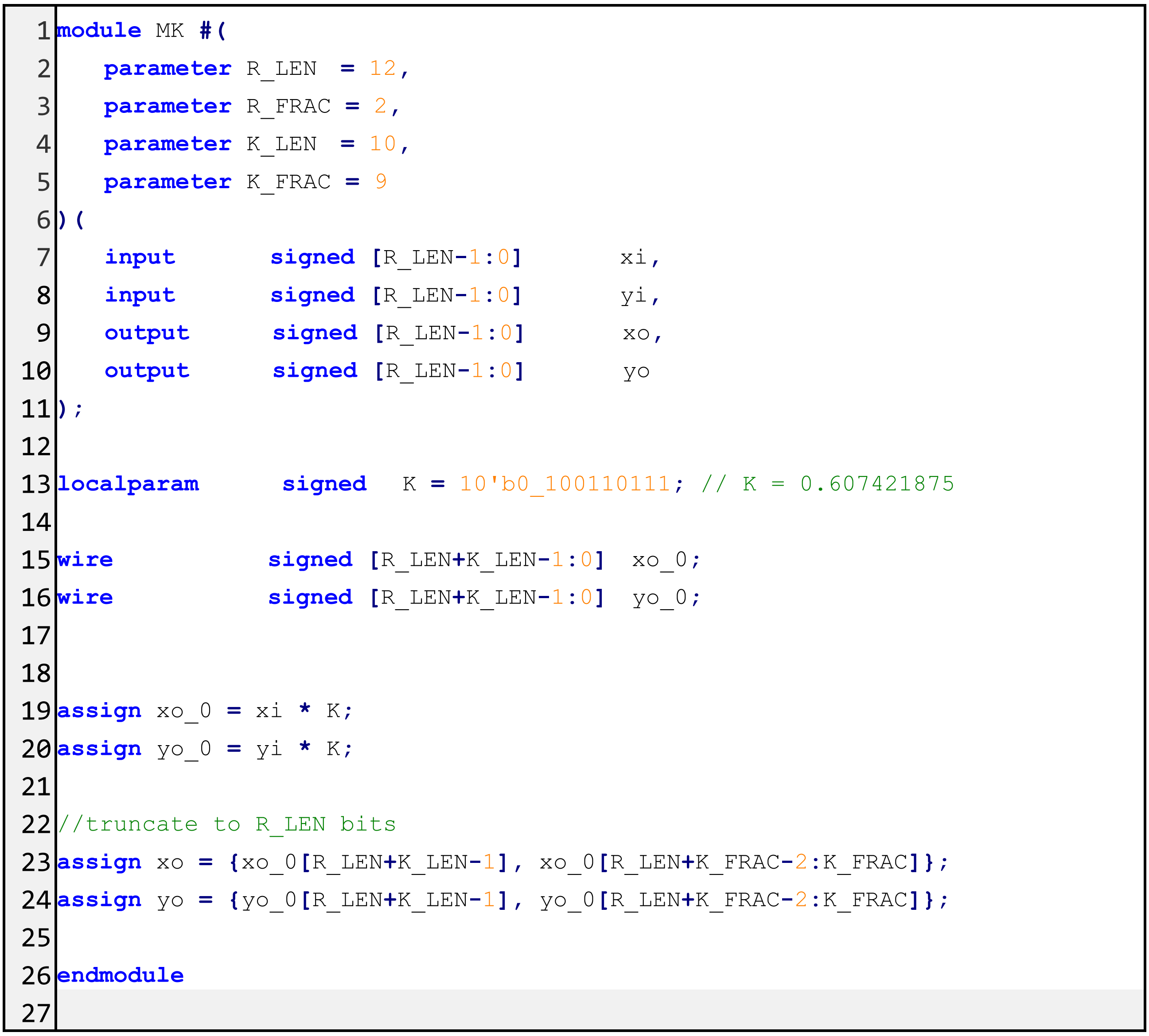
b. GR module



```verilog
module GR_one_iter #(
    parameter R_LEN  = 12,
    parameter R_FRAC = 2
)
(   input       signed [R_LEN-1:0]     xi,
    input       signed [R_LEN-1:0]     yi,
    input              [3:0]          iter,
    input              [1:0]          d,
    output  reg  signed [R_LEN-1:0]    xo,
    output  reg  signed [R_LEN-1:0]    yo
);

always @(*) begin
    if(d == 2) begin
        xo = xi;
        yo = yi;
    end
    else if(d == 1) begin
        xo = xi - (yi >>> iter);
        yo = yi + (xi >>> iter);
    end
    else begin
        xo = xi + (yi >>> iter);
        yo = yi - (xi >>> iter);
    end
end

endmodule
```

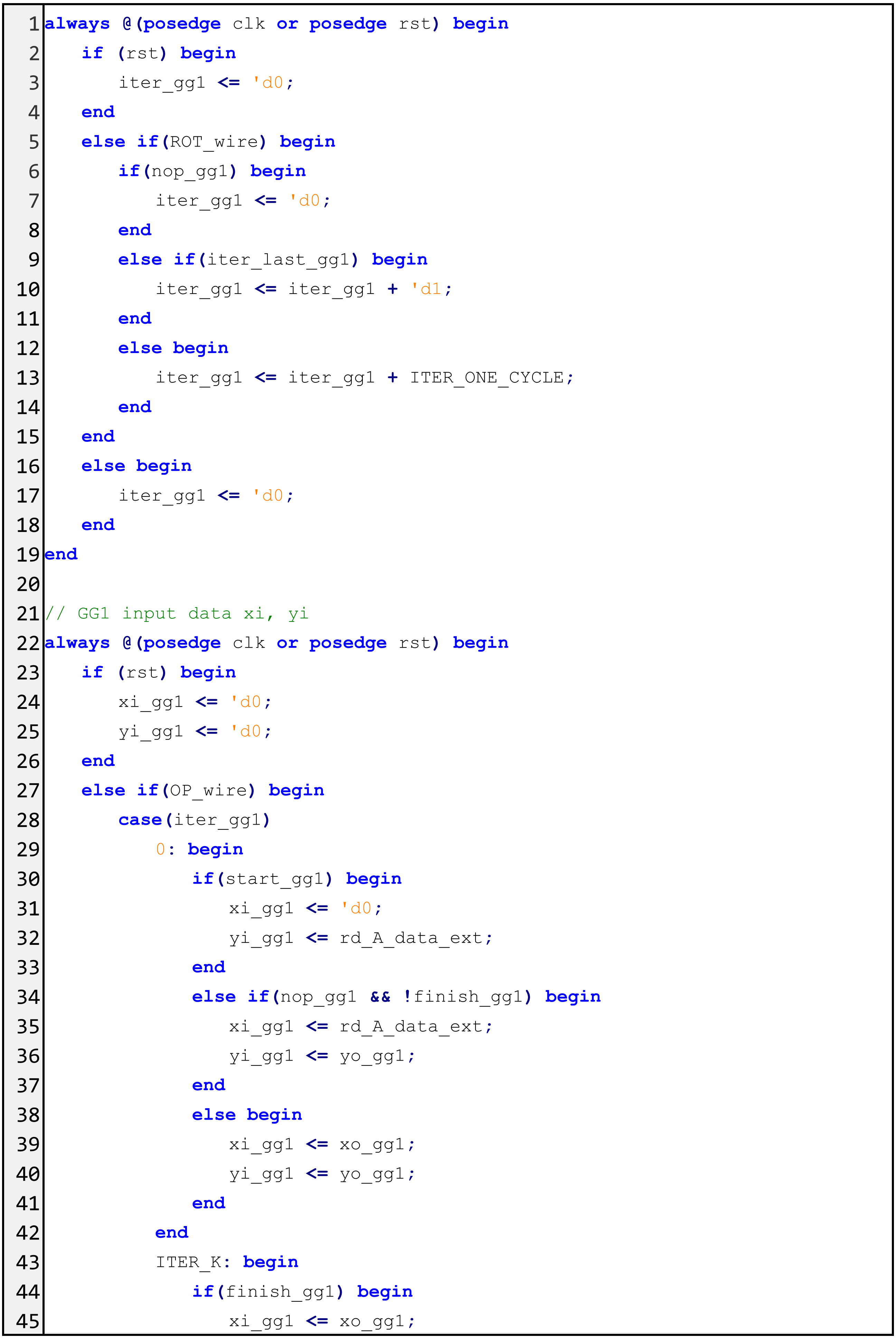
c. Q module is the same as GR

d. MK (multiplied by K)



```
module MK #(
    parameter R_LEN  = 12,
    parameter R_FRAC = 2,
    parameter K_LEN  = 10,
    parameter K_FRAC = 9
)(
    input       signed [R_LEN-1:0]       xi,
    input       signed [R_LEN-1:0]       yi,
    output      signed [R_LEN-1:0]       xo,
    output      signed [R_LEN-1:0]       yo
);

localparam      signed   K = 10'b0_100110111; // K = 0.607421875

wire            signed [R_LEN+K_LEN-1:0]  xo_0;
wire            signed [R_LEN+K_LEN-1:0]  yo_0;


assign xo_0 = xi * K;
assign yo_0 = yi * K;

//truncate to R_LEN bits
assign xo = {xo_0[R_LEN+K_LEN-1], xo_0[R_LEN+K_FRAC-2:K_FRAC]};
assign yo = {yo_0[R_LEN+K_LEN-1], yo_0[R_LEN+K_FRAC-2:K_FRAC]};

endmodule

```

e. GG iteration control



```
always @(posedge clk or posedge rst) begin
    if (rst) begin
        iter_gg1 <= 'd0;
    end
    else if(ROT_wire) begin
        if(nop_gg1) begin
            iter_gg1 <= 'd0;
        end
        else if(iter_last_gg1) begin
            iter_gg1 <= iter_gg1 + 'd1;
        end
        else begin
            iter_gg1 <= iter_gg1 + ITER_ONE_CYCLE;
        end
    end
    else begin
        iter_gg1 <= 'd0;
    end
end

// GG1 input data xi, yi
always @(posedge clk or posedge rst) begin
    if (rst) begin
        xi_gg1 <= 'd0;
        yi_gg1 <= 'd0;
    end
    else if(OP_wire) begin
        case(iter_gg1)
            0: begin
                if(start_gg1) begin
                    xi_gg1 <= 'd0;
                    yi_gg1 <= rd_A_data_ext;
                end
                else if(nop_gg1 && !finish_gg1) begin
                    xi_gg1 <= rd_A_data_ext;
                    yi_gg1 <= yo_gg1;
                end
                else begin
                    xi_gg1 <= xo_gg1;
                    yi_gg1 <= yo_gg1;
                end
            end
            ITER_K: begin
                if(finish_gg1) begin
                    xi_gg1 <= xo_gg1;
                    yi_gg1 <= yo_gg1;
                end
                else begin
                    xi_gg1 <= rd_A_data_ext;
                    yi_gg1 <= xo_mk1;
                end
            end
            default: begin
                xi_gg1 <= xo_gg1;
                yi_gg1 <= yo_gg1;
            end
        endcase
    end
    else begin
        xi_gg1 <= 'd0;
        yi_gg1 <= 'd0;
    end
end

// GG1 mk_count
always @(posedge clk or posedge rst) begin
    if (rst) begin
        mk_count_gg1 <= 'd0;
    end
    else if(multk_gg1) begin
        mk_count_gg1 <= mk_count_gg1 + 'd1;
    end
end
```

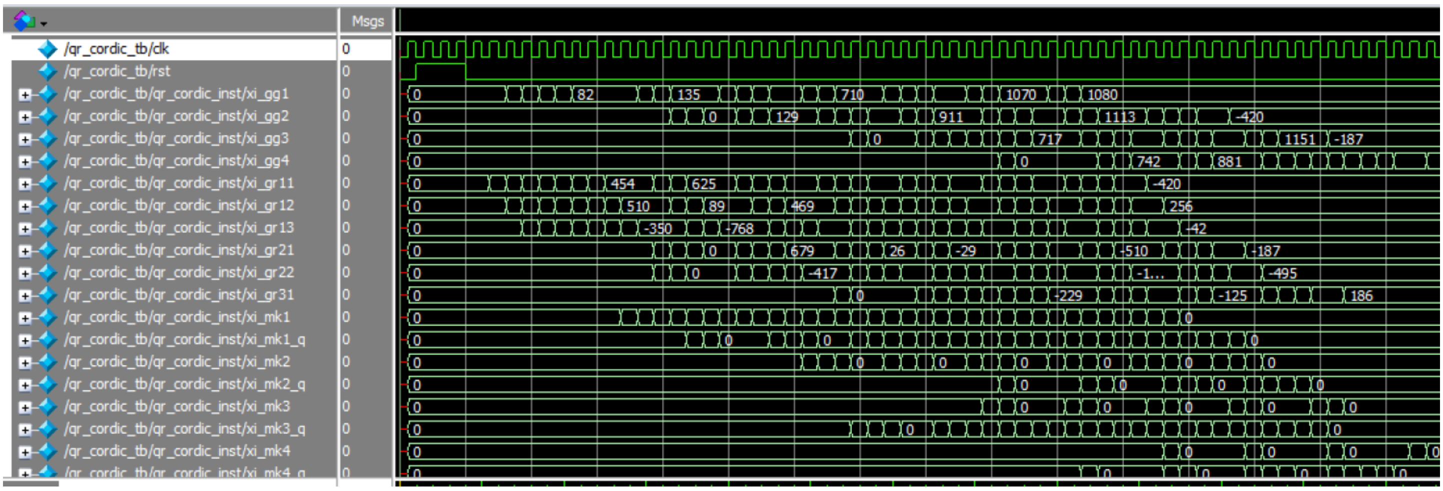
f. GR iteration control

```
// GR11 current iteration number
always @(posedge clk or posedge rst) begin
    if (rst) begin
        iter_gr11  <= 'd0;
        nop_gr11   <= 'd0;
        d1_gr11    <= 'd0;
        d2_gr11    <= 'd0;
        d3_gr11    <= 'd0;
        d4_gr11    <= 'd0;
        neg_gr11   <= 'd0;
        mk_count_gr11 <= 'd0;
    end
    else begin
        iter_gr11  <= iter_gg1;
        nop_gr11   <= nop_gg1;
        d1_gr11    <= d1_gg1;
        d2_gr11    <= d2_gg1;
        d3_gr11    <= d3_gg1;
        d4_gr11    <= d4_gg1;
        neg_gr11   <= neg_gg1;
        mk_count_gr11 <= mk_count_gg1;
    end
end

// GR11 input data xi, yi
always @(posedge clk or posedge rst) begin
    if (rst) begin
        xi_gr11 <= 'd0;
        yi_gr11 <= 'd0;
    end
    else if(OP_wire) begin
        case(iter_gr11)
            0: begin
                if(start_gr11_reg) begin
                    xi_gr11 <= 'd0;
                    yi_gr11 <= rd_A_data_ext;
                end
                else if(nop_gr11 && !finish_gr11) begin
                    xi_gr11 <= rd_A_data_ext;
                    yi_gr11 <= yo_gr11;
                end
                else begin
                    xi_gr11 <= xo_gr11;
                    yi_gr11 <= yo_gr11;
                end
            end
            ITER_K: begin
                if(finish_gr11) begin
                    xi_gr11 <= xo_mk1;
                    yi_gr11 <= yo_mk1;
                end
                else begin
                    xi_gr11 <= rd_A_data_ext;
                    yi_gr11 <= xo_mk1;
                end
            end
            default: begin
                xi_gr11 <= xo_gr11;
                yi_gr11 <= yo_gr11;
            end
        endcase
    end
    else begin
        xi_gr11 <= 'd0;
        xi_gr11 <= 'd0;
    end
end
```

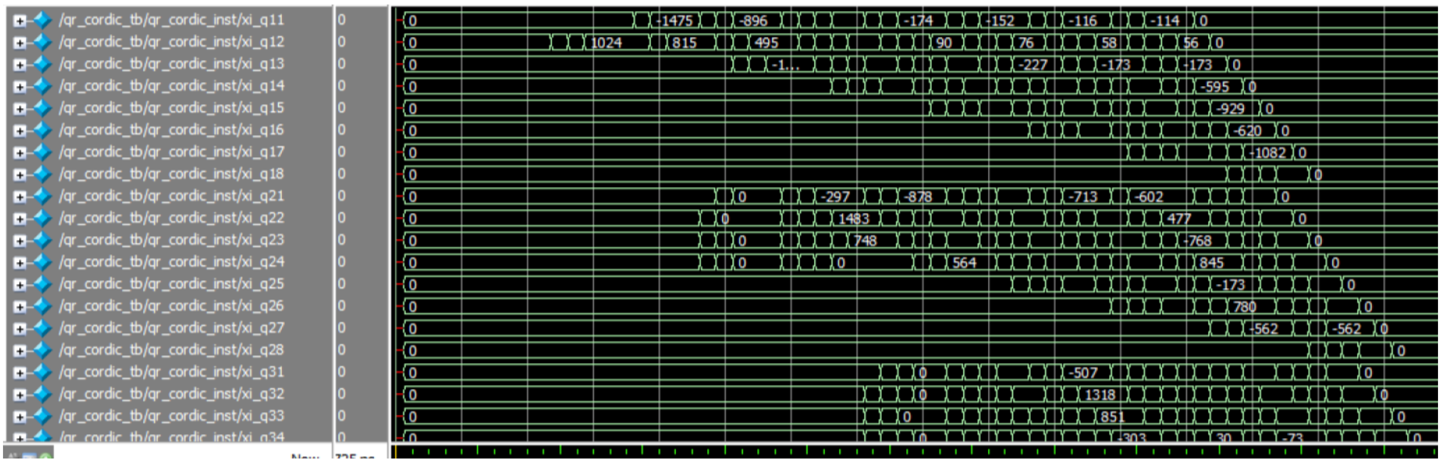
3. Simulation result

a. simulation waveform

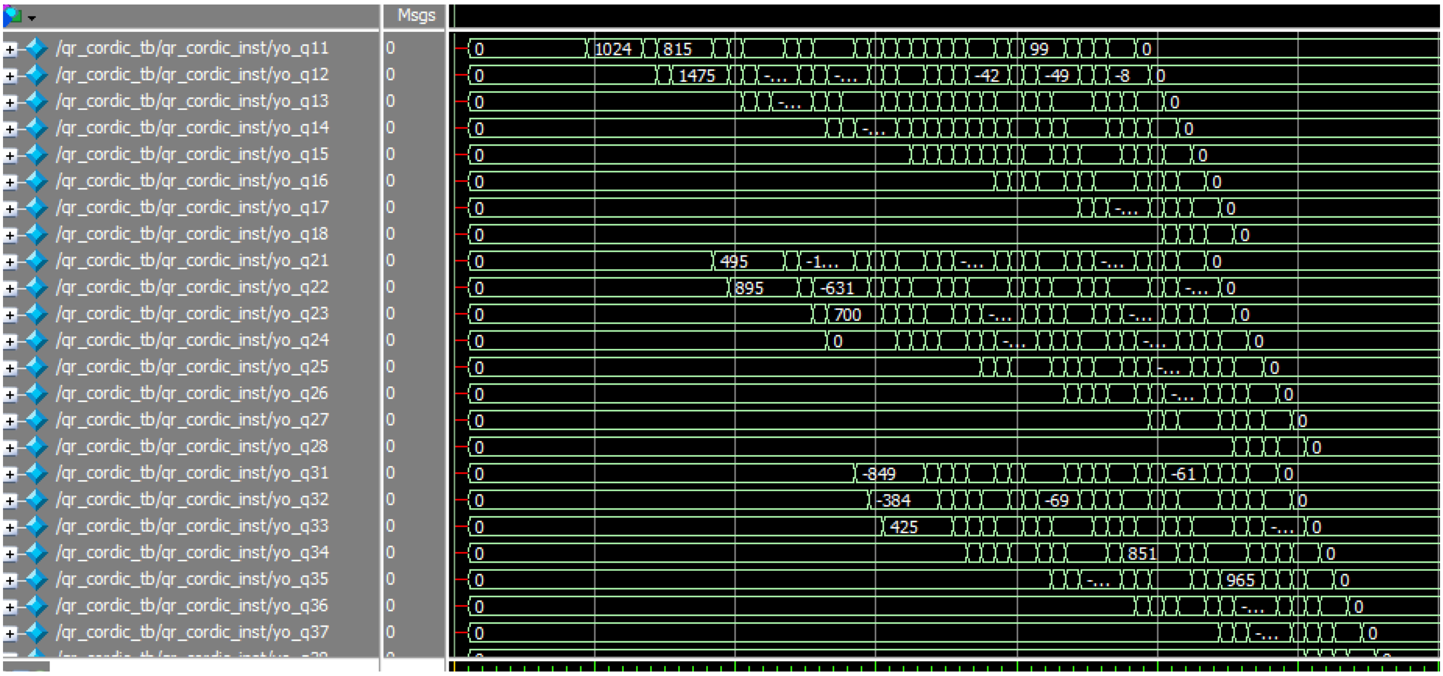
- Data propagate form left to right PE(GG, GR, Q)


Msgs
/qr_cordic_tb/clk
/qr_cordic_tb/rst
/qr_cordic_tb/qr_cordic_inst/xi_gg1
/qr_cordic_tb/qr_cordic_inst/xi_gg2
/qr_cordic_tb/qr_cordic_inst/xi_gg3
/qr_cordic_tb/qr_cordic_inst/xi_gg4
/qr_cordic_tb/qr_cordic_inst/xi_gr11
/qr_cordic_tb/qr_cordic_inst/xi_gr12
/qr_cordic_tb/qr_cordic_inst/xi_gr13
/qr_cordic_tb/qr_cordic_inst/xi_gr21
/qr_cordic_tb/qr_cordic_inst/xi_gr22
/qr_cordic_tb/qr_cordic_inst/xi_gr31
/qr_cordic_tb/qr_cordic_inst/xi_mk1
/qr_cordic_tb/qr_cordic_inst/xi_mk1_q
/qr_cordic_tb/qr_cordic_inst/xi_mk2
/qr_cordic_tb/qr_cordic_inst/xi_mk2_q
/qr_cordic_tb/qr_cordic_inst/xi_mk3
/qr_cordic_tb/qr_cordic_inst/xi_mk3_q
/qr_cordic_tb/qr_cordic_inst/xi_mk4
/qr_cordic_tb/qr_cordic_inst/xi_mk4_q

- Process matrix R


/qr_cordic_tb/qr_cordic_inst/xi_q11
/qr_cordic_tb/qr_cordic_inst/xi_q12
/qr_cordic_tb/qr_cordic_inst/xi_q13
/qr_cordic_tb/qr_cordic_inst/xi_q14
/qr_cordic_tb/qr_cordic_inst/xi_q15
/qr_cordic_tb/qr_cordic_inst/xi_q16
/qr_cordic_tb/qr_cordic_inst/xi_q17
/qr_cordic_tb/qr_cordic_inst/xi_q18
/qr_cordic_tb/qr_cordic_inst/xi_q21
/qr_cordic_tb/qr_cordic_inst/xi_q22
/qr_cordic_tb/qr_cordic_inst/xi_q23
/qr_cordic_tb/qr_cordic_inst/xi_q24
/qr_cordic_tb/qr_cordic_inst/xi_q25
/qr_cordic_tb/qr_cordic_inst/xi_q26
/qr_cordic_tb/qr_cordic_inst/xi_q27
/qr_cordic_tb/qr_cordic_inst/xi_q28
/qr_cordic_tb/qr_cordic_inst/xi_q31
/qr_cordic_tb/qr_cordic_inst/xi_q32
/qr_cordic_tb/qr_cordic_inst/xi_q33
/qr_cordic_tb/qr_cordic_inst/xi_q34

- Process matrix Q


Msgs
/qr_cordic_tb/qr_cordic_inst/yo_q11
/qr_cordic_tb/qr_cordic_inst/yo_q12
/qr_cordic_tb/qr_cordic_inst/yo_q13
/qr_cordic_tb/qr_cordic_inst/yo_q14
/qr_cordic_tb/qr_cordic_inst/yo_q15
/qr_cordic_tb/qr_cordic_inst/yo_q16
/qr_cordic_tb/qr_cordic_inst/yo_q17
/qr_cordic_tb/qr_cordic_inst/yo_q18
/qr_cordic_tb/qr_cordic_inst/yo_q21
/qr_cordic_tb/qr_cordic_inst/yo_q22
/qr_cordic_tb/qr_cordic_inst/yo_q23
/qr_cordic_tb/qr_cordic_inst/yo_q24
/qr_cordic_tb/qr_cordic_inst/yo_q25
/qr_cordic_tb/qr_cordic_inst/yo_q26
/qr_cordic_tb/qr_cordic_inst/yo_q27
/qr_cordic_tb/qr_cordic_inst/yo_q28
/qr_cordic_tb/qr_cordic_inst/yo_q31
/qr_cordic_tb/qr_cordic_inst/yo_q32
/qr_cordic_tb/qr_cordic_inst/yo_q33
/qr_cordic_tb/qr_cordic_inst/yo_q34
/qr_cordic_tb/qr_cordic_inst/yo_q35
/qr_cordic_tb/qr_cordic_inst/yo_q36
/qr_cordic_tb/qr_cordic_inst/yo_q37

- Data flow & data scheduling

GG1→GR11→GR12→GR13→Q11→Q12→Q13→…..→Q18

-------- GG2→GR21→GR22→Q21→Q22→Q23→…..→Q28

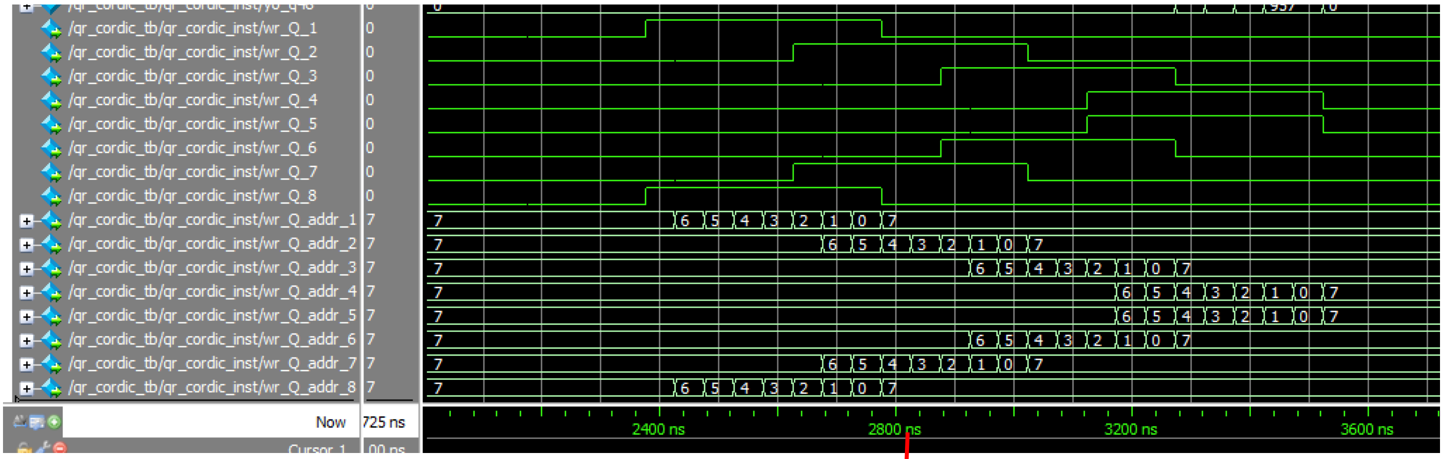
---------------- GG3→GR31→Q31→Q32→Q33→…..→Q38

-------------------------- GG4→Q41→Q42→Q43→…..→Q48

- timing diagram

GG1		N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N											
GR11			N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N										
GR12				N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N									
GR13					N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N								
MK1										K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K								
Q11						N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N							
Q12							N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N						
Q13								N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N					
Q14									N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N				
Q15										N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N			
Q16											N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N		
Q17												N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N	
Q18													N	N	N	N	78	78	78	78	N	67	67	67	67	N	56	56	56	56	N	45	45	45	45	N	34	34	34	34	N	23	23	23	23	N	12	12	12	12	N
MK1_Q																		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K		K	K	K	K

- Write Q matrix data back



/qr_cordic_tb/qr_cordic_inst/wr_Q_1 0
/qr_cordic_tb/qr_cordic_inst/wr_Q_2 0
/qr_cordic_tb/qr_cordic_inst/wr_Q_3 0
/qr_cordic_tb/qr_cordic_inst/wr_Q_4 0
/qr_cordic_tb/qr_cordic_inst/wr_Q_5 0
/qr_cordic_tb/qr_cordic_inst/wr_Q_6 0
/qr_cordic_tb/qr_cordic_inst/wr_Q_7 0
/qr_cordic_tb/qr_cordic_inst/wr_Q_8 0
/qr_cordic_tb/qr_cordic_inst/wr_Q_addr_1 7
/qr_cordic_tb/qr_cordic_inst/wr_Q_addr_2 7
/qr_cordic_tb/qr_cordic_inst/wr_Q_addr_3 7
/qr_cordic_tb/qr_cordic_inst/wr_Q_addr_4 7
/qr_cordic_tb/qr_cordic_inst/wr_Q_addr_5 7
/qr_cordic_tb/qr_cordic_inst/wr_Q_addr_6 7
/qr_cordic_tb/qr_cordic_inst/wr_Q_addr_7 7
/qr_cordic_tb/qr_cordic_inst/wr_Q_addr_8 7

Now 725 ns

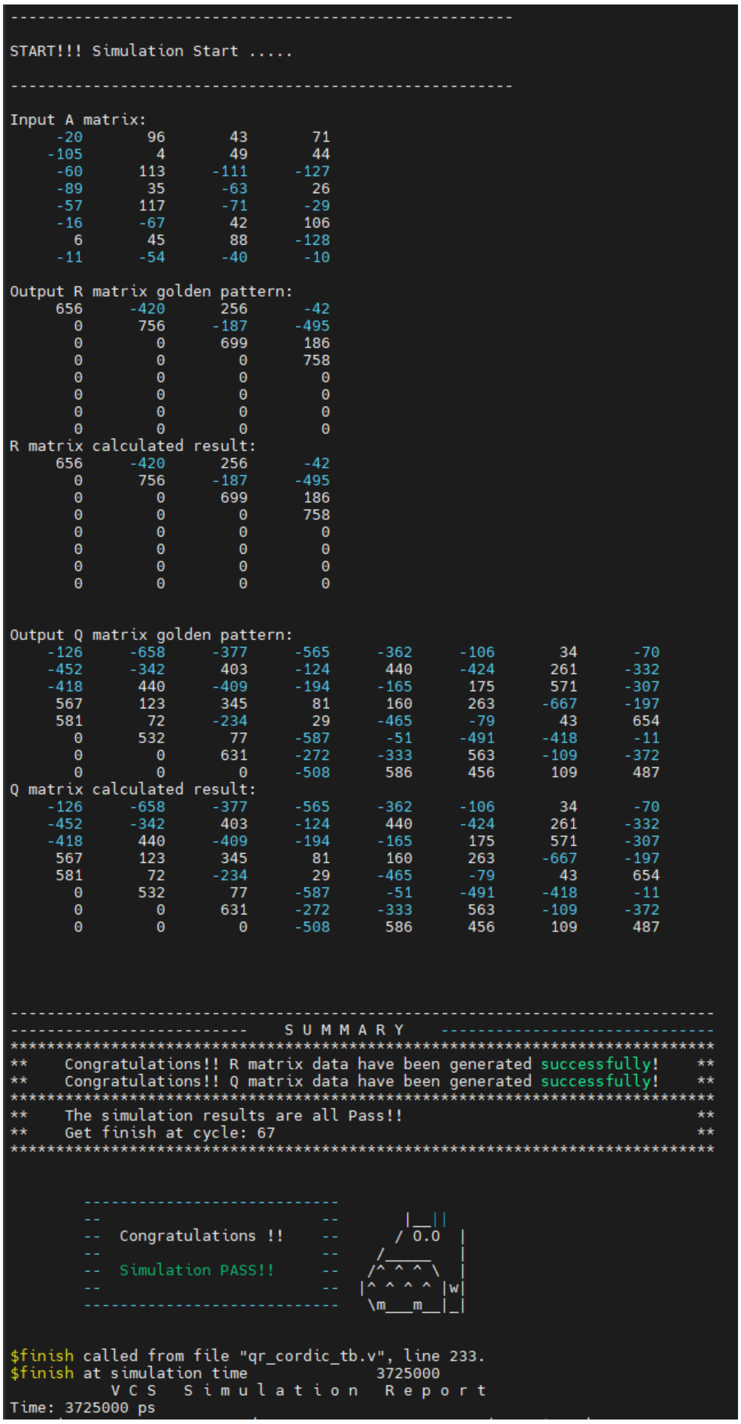
Each row has an independent write enable signal, since multiple data outputs from Q occur simultaneously in the systolic array.

- Timing diagram

	11	12	13	14	15	16	17	18														
					21	22	23	24	25	26	27	28										
										31	32	33	34	35	36	37	38					
															41	42	43	44	45	46	47	48
															51	52	53	54	55	56	57	58
										61	62	63	64	65	66	67	68					
					71	72	73	74	75	76	77	78										
	81	82	83	84	85	86	87	88														
																						F

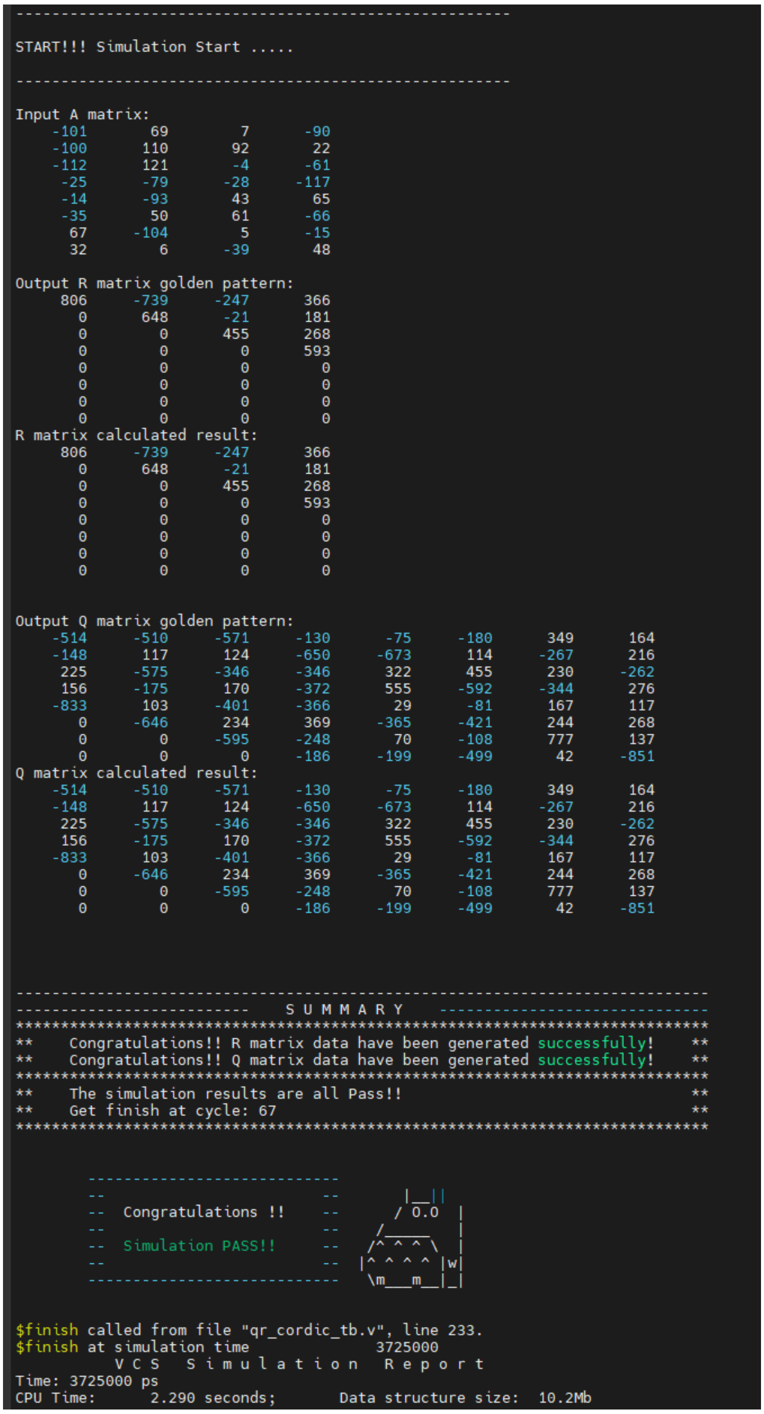
b. RTL simulation

Pattern 1:



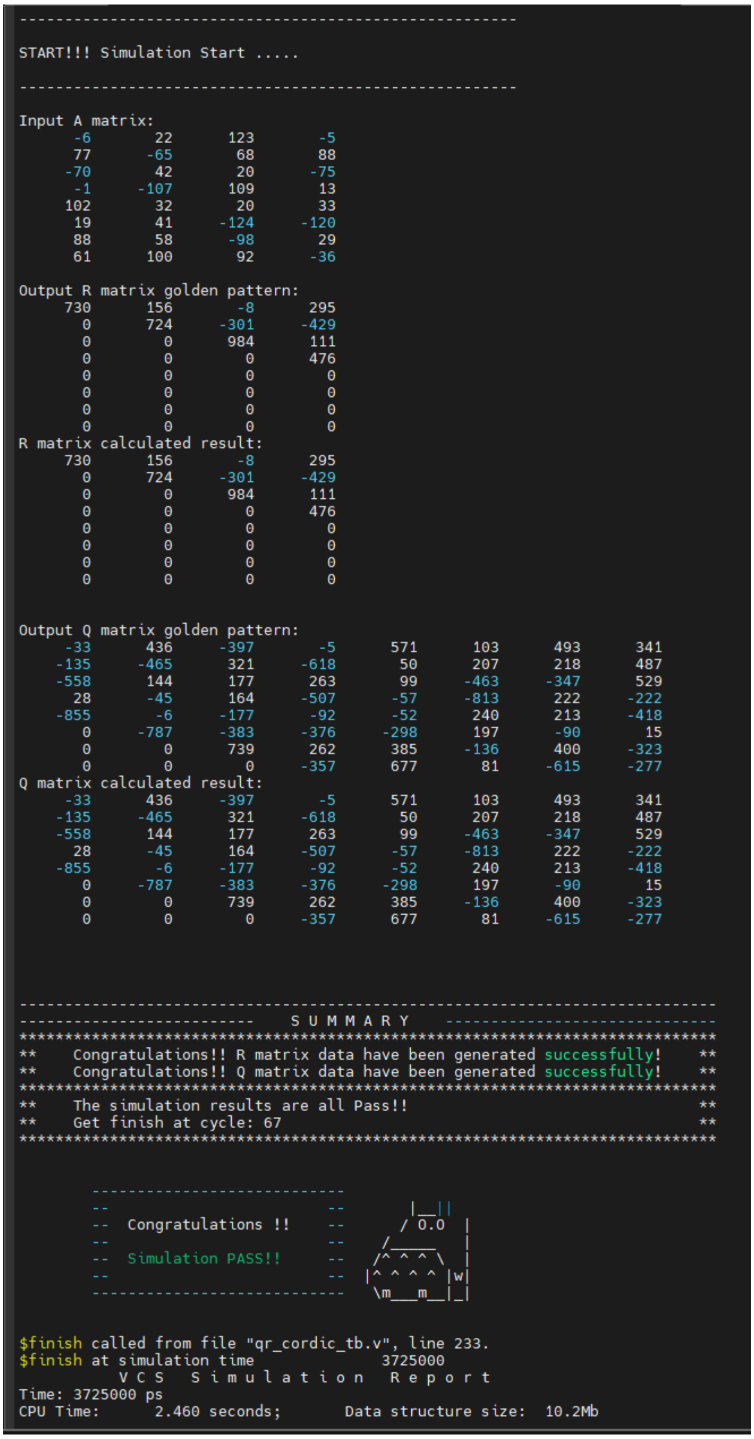
```
-------------------------------------------------------

START!!! Simulation Start .....

-------------------------------------------------------

Input A matrix:
     -20        96        43        71
    -105         4        49        44
     -60       113      -111      -127
     -89        35       -63        26
     -57       117       -71       -29
     -16       -67        42       106
       6        45        88      -128
     -11       -54       -40       -10

Output R matrix golden pattern:
     656      -420       256       -42
       0       756      -187      -495
       0         0       699       186
       0         0         0       758
       0         0         0         0
       0         0         0         0
       0         0         0         0
       0         0         0         0
R matrix calculated result:
     656      -420       256       -42
       0       756      -187      -495
       0         0       699       186
       0         0         0       758
       0         0         0         0
       0         0         0         0
       0         0         0         0
       0         0         0         0


Output Q matrix golden pattern:
    -126      -658      -377      -565      -362      -106        34       -70
    -452      -342       403      -124       440      -424       261      -332
    -418       440      -409      -194      -165       175       571      -307
     567       123       345        81       160       263      -667      -197
     581        72      -234        29      -465       -79        43       654
       0       532        77      -587       -51      -491      -418       -11
       0         0       631      -272      -333       563      -109      -372
       0         0         0      -508       586       456       109       487
Q matrix calculated result:
    -126      -658      -377      -565      -362      -106        34       -70
    -452      -342       403      -124       440      -424       261      -332
    -418       440      -409      -194      -165       175       571      -307
     567       123       345        81       160       263      -667      -197
     581        72      -234        29      -465       -79        43       654
       0       532        77      -587       -51      -491      -418       -11
       0         0       631      -272      -333       563      -109      -372
       0         0         0      -508       586       456       109       487



-----------------------------------------------------------------------------
--------------------------   S U M M A R Y   --------------------------------
*****************************************************************************
**     Congratulations!! R matrix data have been generated successfully!    **
**     Congratulations!! Q matrix data have been generated successfully!    **
*****************************************************************************
**     The simulation results are all Pass!!                                **
**     Get finish at cycle: 67                                              **
*****************************************************************************



        ----------------------------
        --                        --       |__||
        --  Congratulations !!    --      / 0.0  |
        --                        --    /______  |
        --  Simulation PASS!!     --   /^ ^ ^ \  |
        --                        --  |^ ^ ^ ^ |w|
        ----------------------------   \m___m__|_|


$finish called from file "qr_cordic_tb.v", line 233.
$finish at simulation time                 3725000
           V C S   S i m u l a t i o n   R e p o r t
Time: 3725000 ps
```

Pattern 2:



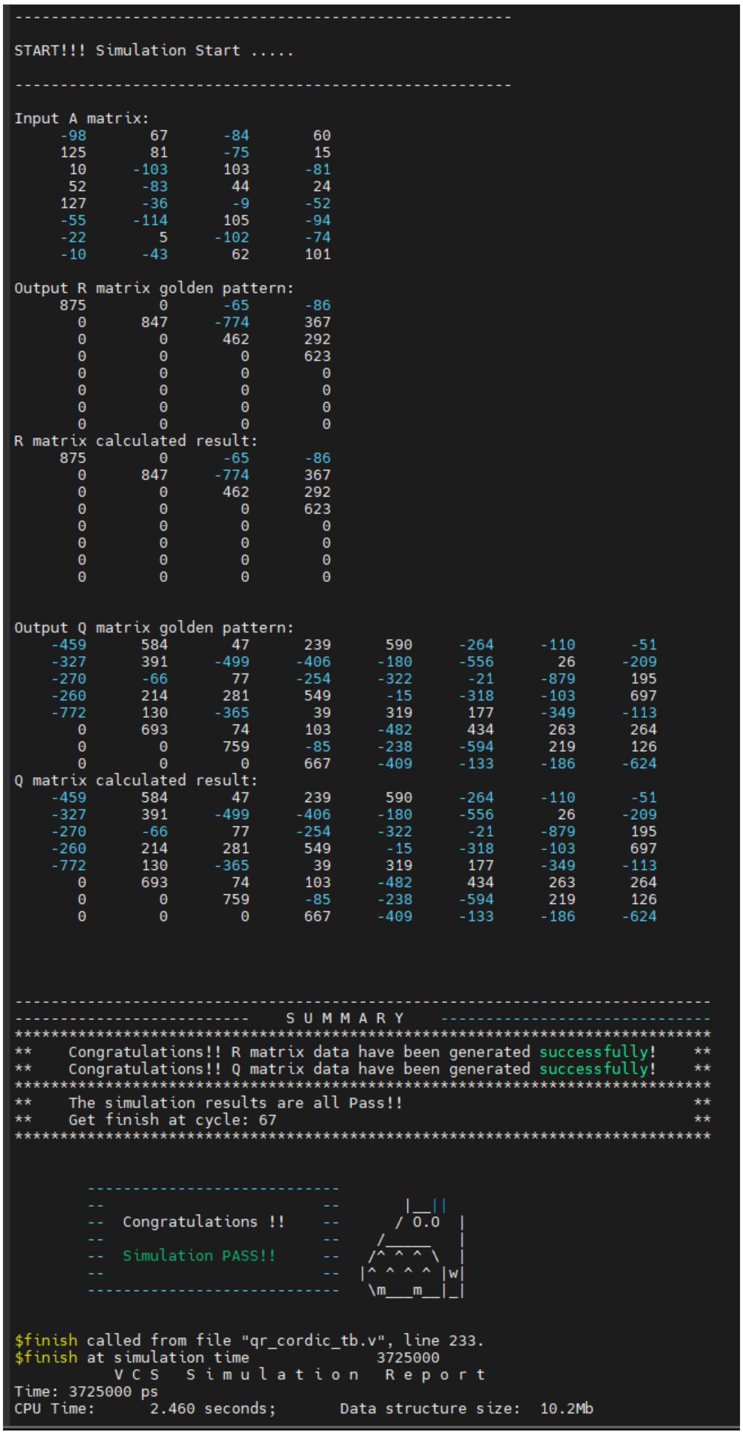
```
-------------------------------------------------------

START!!! Simulation Start .....

-------------------------------------------------------

Input A matrix:
    -101        69         7       -90
    -100       110        92        22
    -112       121        -4       -61
     -25       -79       -28      -117
     -14       -93        43        65
     -35        50        61       -66
      67      -104         5       -15
      32         6       -39        48

Output R matrix golden pattern:
     806      -739      -247       366
       0       648       -21       181
       0         0       455       268
       0         0         0       593
       0         0         0         0
       0         0         0         0
       0         0         0         0
       0         0         0         0
R matrix calculated result:
     806      -739      -247       366
       0       648       -21       181
       0         0       455       268
       0         0         0       593
       0         0         0         0
       0         0         0         0
       0         0         0         0
       0         0         0         0


Output Q matrix golden pattern:
    -514      -510      -571      -130       -75      -180       349       164
    -148       117       124      -650      -673       114      -267       216
     225      -575      -346      -346       322       455       230      -262
     156      -175       170      -372       555      -592      -344       276
    -833       103      -401      -366        29       -81       167       117
       0      -646       234       369      -365      -421       244       268
       0         0      -595      -248        70      -108       777       137
       0         0         0      -186      -199      -499        42      -851
Q matrix calculated result:
    -514      -510      -571      -130       -75      -180       349       164
    -148       117       124      -650      -673       114      -267       216
     225      -575      -346      -346       322       455       230      -262
     156      -175       170      -372       555      -592      -344       276
    -833       103      -401      -366        29       -81       167       117
       0      -646       234       369      -365      -421       244       268
       0         0      -595      -248        70      -108       777       137
       0         0         0      -186      -199      -499        42      -851



-----------------------------------------------------------------------------
--------------------------   S U M M A R Y   --------------------------------
*****************************************************************************
**     Congratulations!! R matrix data have been generated successfully!    **
**     Congratulations!! Q matrix data have been generated successfully!    **
*****************************************************************************
**     The simulation results are all Pass!!                                **
**     Get finish at cycle: 67                                              **
*****************************************************************************



        ----------------------------
        --                        --       |__||
        --  Congratulations !!    --      / 0.0  |
        --                        --    /______  |
        --  Simulation PASS!!     --   /^ ^ ^ \  |
        --                        --  |^ ^ ^ ^ |w|
        ----------------------------   \m___m__|_|


$finish called from file "qr_cordic_tb.v", line 233.
$finish at simulation time                 3725000
           V C S   S i m u l a t i o n   R e p o r t
Time: 3725000 ps
CPU Time:      2.290 seconds;       Data structure size:   10.2Mb
```

Pattern 3:



```
-------------------------------------------------------

START!!! Simulation Start .....

-------------------------------------------------------

Input A matrix:
      -6      22     123      -5
      77     -65      68      88
     -70      42      20     -75
      -1    -107     109      13
     102      32      20      33
      19      41    -124    -120
      88      58     -98      29
      61     100      92     -36

Output R matrix golden pattern:
     730     156      -8     295
       0     724    -301    -429
       0       0     984     111
       0       0       0     476
       0       0       0       0
       0       0       0       0
       0       0       0       0
       0       0       0       0
R matrix calculated result:
     730     156      -8     295
       0     724    -301    -429
       0       0     984     111
       0       0       0     476
       0       0       0       0
       0       0       0       0
       0       0       0       0
       0       0       0       0


Output Q matrix golden pattern:
     -33     436    -397      -5     571     103     493     341
    -135    -465     321    -618      50     207     218     487
    -558     144     177     263      99    -463    -347     529
      28     -45     164    -507     -57    -813     222    -222
    -855      -6    -177     -92     -52     240     213    -418
       0    -787    -383    -376    -298     197     -90      15
       0       0     739     262     385    -136     400    -323
       0       0       0    -357     677      81    -615    -277
Q matrix calculated result:
     -33     436    -397      -5     571     103     493     341
    -135    -465     321    -618      50     207     218     487
    -558     144     177     263      99    -463    -347     529
      28     -45     164    -507     -57    -813     222    -222
    -855      -6    -177     -92     -52     240     213    -418
       0    -787    -383    -376    -298     197     -90      15
       0       0     739     262     385    -136     400    -323
       0       0       0    -357     677      81    -615    -277



----------------------------------------------------------------------------
--------------------------    S U M M A R Y    -----------------------------
****************************************************************************
**    Congratulations!! R matrix data have been generated successfully!   **
**    Congratulations!! Q matrix data have been generated successfully!   **
****************************************************************************
**    The simulation results are all Pass!!                               **
**    Get finish at cycle: 67                                             **
****************************************************************************


        ----------------------------
        --                        --       |__||
        --  Congratulations !!    --      / O.O  |
        --                        --    /_____   |
        --  Simulation PASS!!     --   /^ ^ ^ \  |
        --                        --  |^ ^ ^ ^ |w|
        ----------------------------   \m___m__|_|


$finish called from file "qr_cordic_tb.v", line 233.
$finish at simulation time              3725000
           V C S   S i m u l a t i o n   R e p o r t
Time: 3725000 ps
CPU Time:      2.460 seconds;       Data structure size:  10.2Mb
```

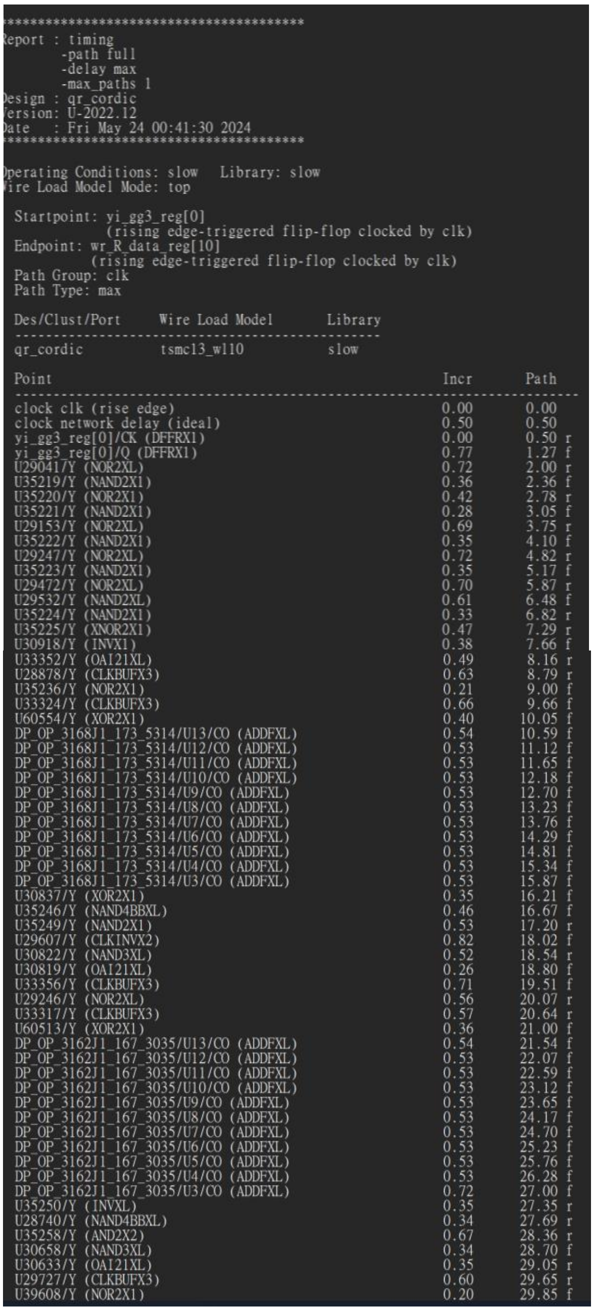
Pattern4:



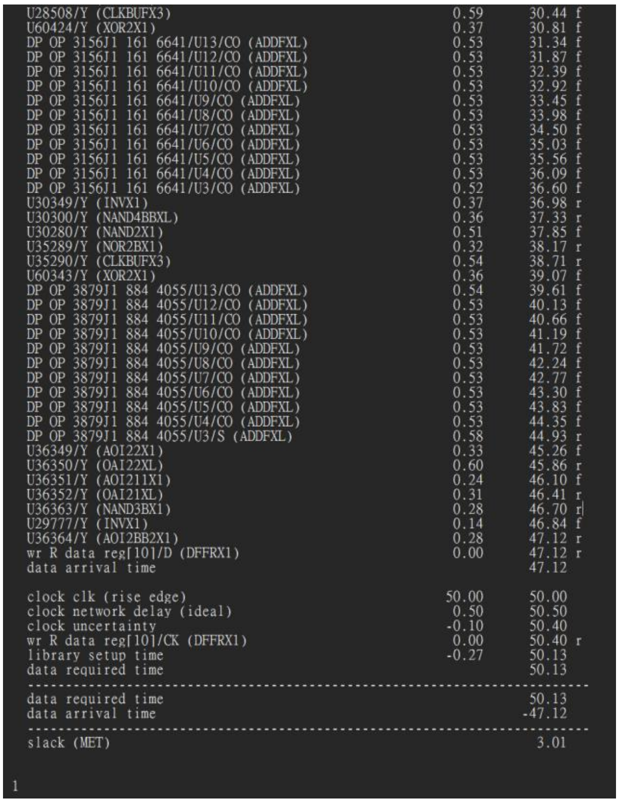
```
-------------------------------------------------------

START!!! Simulation Start .....

-------------------------------------------------------

Input A matrix:
     -98      67     -84      60
     125      81     -75      15
      10    -103     103     -81
      52     -83      44      24
     127     -36      -9     -52
     -55    -114     105     -94
     -22       5    -102     -74
     -10     -43      62     101

Output R matrix golden pattern:
     875       0     -65     -86
       0     847    -774     367
       0       0     462     292
       0       0       0     623
       0       0       0       0
       0       0       0       0
       0       0       0       0
       0       0       0       0
R matrix calculated result:
     875       0     -65     -86
       0     847    -774     367
       0       0     462     292
       0       0       0     623
       0       0       0       0
       0       0       0       0
       0       0       0       0
       0       0       0       0


Output Q matrix golden pattern:
    -459     584      47     239     590    -264    -110     -51
    -327     391    -499    -406    -180    -556      26    -209
    -270     -66      77    -254    -322     -21    -879     195
    -260     214     281     549     -15    -318    -103     697
    -772     130    -365      39     319     177    -349    -113
       0     693      74     103    -482     434     263     264
       0       0     759     -85    -238    -594     219     126
       0       0       0     667    -409    -133    -186    -624
Q matrix calculated result:
    -459     584      47     239     590    -264    -110     -51
    -327     391    -499    -406    -180    -556      26    -209
    -270     -66      77    -254    -322     -21    -879     195
    -260     214     281     549     -15    -318    -103     697
    -772     130    -365      39     319     177    -349    -113
       0     693      74     103    -482     434     263     264
       0       0     759     -85    -238    -594     219     126
       0       0       0     667    -409    -133    -186    -624



----------------------------------------------------------------------------
--------------------------    S U M M A R Y    -----------------------------
****************************************************************************
**    Congratulations!! R matrix data have been generated successfully!   **
**    Congratulations!! Q matrix data have been generated successfully!   **
****************************************************************************
**    The simulation results are all Pass!!                               **
**    Get finish at cycle: 67                                             **
****************************************************************************


        ----------------------------
        --                        --       |__||
        --  Congratulations !!    --      / O.O  |
        --                        --    /_____   |
        --  Simulation PASS!!     --   /^ ^ ^ \  |
        --                        --  |^ ^ ^ ^ |w|
        ----------------------------   \m___m__|_|


$finish called from file "qr_cordic_tb.v", line 233.
$finish at simulation time              3725000
           V C S   S i m u l a t i o n   R e p o r t
Time: 3725000 ps
CPU Time:      2.460 seconds;       Data structure size:  10.2Mb
```

c. synthesis report (clock rate = 50ns)

i. timing report

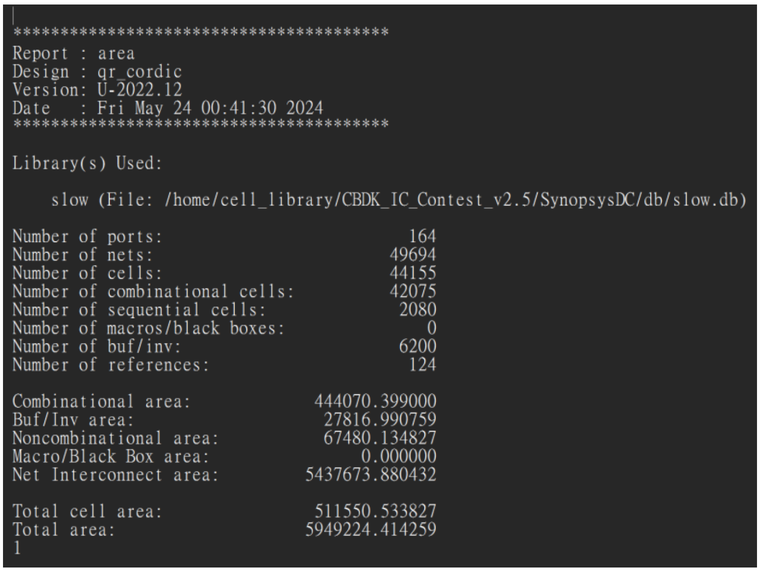


```
****************************************
eport : timing
       -path full
       -delay max
       -max_paths 1
esign : qr_cordic
ersion: U-2022.12
ate   : Fri May 24 00:41:30 2024
****************************************

perating Conditions: slow   Library: slow
ire Load Model Mode: top

  Startpoint: yi_gg3_reg[0]
              (rising edge-triggered flip-flop clocked by clk)
  Endpoint: wr_R_data_reg[10]
            (rising edge-triggered flip-flop clocked by clk)
  Path Group: clk
  Path Type: max

  Des/Clust/Port     Wire Load Model       Library
  ------------------------------------------------
  qr_cordic          tsmc13_wl10           slow

  Point                                                   Incr       Path
  --------------------------------------------------------------------------
  clock clk (rise edge)                                   0.00       0.00
  clock network delay (ideal)                             0.50       0.50
  yi_gg3_reg[0]/CK (DFFRX1)                               0.00       0.50 r
  yi_gg3_reg[0]/Q (DFFRX1)                                0.77       1.27 f
  U290417/Y (NOR2XL)                                      0.72       2.00 r
  U35219/Y (NAND2X1)                                      0.36       2.36 f
  U35220/Y (NOR2X1)                                       0.42       2.78 r
  U35221/Y (NAND2X1)                                      0.28       3.05 f
  U29153/Y (NOR2XL)                                       0.69       3.75 r
  U35222/Y (NAND2X1)                                      0.35       4.10 f
  U29247/Y (NOR2XL)                                       0.72       4.82 r
  U35223/Y (NAND2X1)                                      0.35       5.17 f
  U29472/Y (NOR2XL)                                       0.70       5.87 r
  U29532/Y (NAND2XL)                                      0.61       6.48 f
  U35224/Y (NAND2X1)                                      0.33       6.82 r
  U35225/Y (XNOR2X1)                                      0.47       7.29 r
  U30918/Y (INVX1)                                        0.38       7.66 f
  U33352/Y (OAI21XL)                                      0.49       8.16 r
  U28878/Y (CLKBUFX3)                                     0.63       8.79 r
  U35236/Y (NOR2X1)                                       0.21       9.00 f
  U33324/Y (CLKBUFX3)                                     0.66       9.66 f
  U60554/Y (XOR2X1)                                       0.40      10.05 f
  DP_OP_3168J1_173_5314/U13/CO (ADDFXL)                   0.54      10.59 f
  DP_OP_3168J1_173_5314/U12/CO (ADDFXL)                   0.53      11.12 f
  DP_OP_3168J1_173_5314/U11/CO (ADDFXL)                   0.53      11.65 f
  DP_OP_3168J1_173_5314/U10/CO (ADDFXL)                   0.53      12.18 f
  DP_OP_3168J1_173_5314/U9/CO (ADDFXL)                    0.53      12.70 f
  DP_OP_3168J1_173_5314/U8/CO (ADDFXL)                    0.53      13.23 f
  DP_OP_3168J1_173_5314/U7/CO (ADDFXL)                    0.53      13.76 f
  DP_OP_3168J1_173_5314/U6/CO (ADDFXL)                    0.53      14.29 f
  DP_OP_3168J1_173_5314/U5/CO (ADDFXL)                    0.53      14.81 f
  DP_OP_3168J1_173_5314/U4/CO (ADDFXL)                    0.53      15.34 f
  DP_OP_3168J1_173_5314/U3/CO (ADDFXL)                    0.53      15.87 f
  U30837/Y (XOR2X1)                                       0.35      16.21 f
  U35246/Y (NAND4BBXL)                                    0.46      16.67 f
  U35249/Y (NAND2X1)                                      0.53      17.20 r
  U29607/Y (CLKINVX2)                                     0.82      18.02 f
  U30822/Y (NAND3XL)                                      0.52      18.54 r
  U30819/Y (OAI21XL)                                      0.26      18.80 f
  U33356/Y (CLKBUFX3)                                     0.71      19.51 f
  U29246/Y (NOR2XL)                                       0.56      20.07 r
  U33317/Y (CLKBUFX3)                                     0.57      20.64 r
  U60513/Y (XOR2X1)                                       0.36      21.00 f
  DP_OP_3162J1_167_3035/U13/CO (ADDFXL)                   0.54      21.54 f
  DP_OP_3162J1_167_3035/U12/CO (ADDFXL)                   0.53      22.07 f
  DP_OP_3162J1_167_3035/U11/CO (ADDFXL)                   0.53      22.59 f
  DP_OP_3162J1_167_3035/U10/CO (ADDFXL)                   0.53      23.12 f
  DP_OP_3162J1_167_3035/U9/CO (ADDFXL)                    0.53      23.65 f
  DP_OP_3162J1_167_3035/U8/CO (ADDFXL)                    0.53      24.17 f
  DP_OP_3162J1_167_3035/U7/CO (ADDFXL)                    0.53      24.70 f
  DP_OP_3162J1_167_3035/U6/CO (ADDFXL)                    0.53      25.23 f
  DP_OP_3162J1_167_3035/U5/CO (ADDFXL)                    0.53      25.76 f
  DP_OP_3162J1_167_3035/U4/CO (ADDFXL)                    0.53      26.28 f
  DP_OP_3162J1_167_3035/U3/CO (ADDFXL)                    0.72      27.00 f
  U35250/Y (INVXL)                                        0.35      27.35 r
  U28740/Y (NAND4BBXL)                                    0.34      27.69 r
  U35258/Y (AND2X2)                                       0.67      28.36 r
  U30658/Y (NAND3XL)                                      0.34      28.70 f
  U30633/Y (OAI21XL)                                      0.35      29.05 r
  U29727/Y (CLKBUFX3)                                     0.60      29.65 r
  U39608/Y (NOR2X1)                                       0.20      29.85 f
```



```
  U28508/Y (CLKBUFX3)                                     0.59      30.44 f
  U60424/Y (XOR2X1)                                       0.37      30.81 f
  DP OP 3156J1 161 6641/U13/CO (ADDFXL)                   0.53      31.34 f
  DP OP 3156J1 161 6641/U12/CO (ADDFXL)                   0.53      31.87 f
  DP OP 3156J1 161 6641/U11/CO (ADDFXL)                   0.53      32.39 f
  DP OP 3156J1 161 6641/U10/CO (ADDFXL)                   0.53      32.92 f
  DP OP 3156J1 161 6641/U9/CO (ADDFXL)                    0.53      33.45 f
  DP OP 3156J1 161 6641/U8/CO (ADDFXL)                    0.53      33.98 f
  DP OP 3156J1 161 6641/U7/CO (ADDFXL)                    0.53      34.50 f
  DP OP 3156J1 161 6641/U6/CO (ADDFXL)                    0.53      35.03 f
  DP OP 3156J1 161 6641/U5/CO (ADDFXL)                    0.53      35.56 f
  DP OP 3156J1 161 6641/U4/CO (ADDFXL)                    0.53      36.09 f
  DP OP 3156J1 161 6641/U3/CO (ADDFXL)                    0.52      36.60 f
  U30349/Y (INVX1)                                        0.37      36.98 r
  U30300/Y (NAND4BBXL)                                    0.36      37.33 r
  U30280/Y (NAND2X1)                                      0.51      37.85 f
  U35289/Y (NOR2BX1)                                      0.32      38.17 r
  U35290/Y (CLKBUFX3)                                     0.54      38.71 r
  U60343/Y (XOR2X1)                                       0.36      39.07 f
  DP OP 3879J1 884 4055/U13/CO (ADDFXL)                   0.54      39.61 f
  DP OP 3879J1 884 4055/U12/CO (ADDFXL)                   0.53      40.13 f
  DP OP 3879J1 884 4055/U11/CO (ADDFXL)                   0.53      40.66 f
  DP OP 3879J1 884 4055/U10/CO (ADDFXL)                   0.53      41.19 f
  DP OP 3879J1 884 4055/U9/CO (ADDFXL)                    0.53      41.72 f
  DP OP 3879J1 884 4055/U8/CO (ADDFXL)                    0.53      42.24 f
  DP OP 3879J1 884 4055/U7/CO (ADDFXL)                    0.53      42.77 f
  DP OP 3879J1 884 4055/U6/CO (ADDFXL)                    0.53      43.30 f
  DP OP 3879J1 884 4055/U5/CO (ADDFXL)                    0.53      43.83 f
  DP OP 3879J1 884 4055/U4/CO (ADDFXL)                    0.53      44.35 f
  DP OP 3879J1 884 4055/U3/S (ADDFXL)                     0.58      44.93 r
  U36349/Y (AOI22X1)                                      0.33      45.26 f
  U36350/Y (OAI22XL)                                      0.60      45.86 r
  U36351/Y (AOI211X1)                                     0.24      46.10 f
  U36352/Y (OAI21XL)                                      0.31      46.41 r
  U36363/Y (NAND3BX1)                                     0.28      46.70 r
  U29777/Y (INVX1)                                        0.14      46.84 f
  U36364/Y (AOI2BB2X1)                                    0.28      47.12 r
  wr R data reg[10]/D (DFFRX1)                            0.00      47.12 r
  data arrival time                                                 47.12

  clock clk (rise edge)                                  50.00      50.00
  clock network delay (ideal)                             0.50      50.50
  clock uncertainty                                      -0.10      50.40
  wr R data reg[10]/CK (DFFRX1)                           0.00      50.40 r
  library setup time                                     -0.27      50.13
  data required time                                                50.13
  --------------------------------------------------------------------------
  data required time                                                50.13
  data arrival time                                                -47.12
  --------------------------------------------------------------------------
  slack (MET)                                                        3.01


1
```

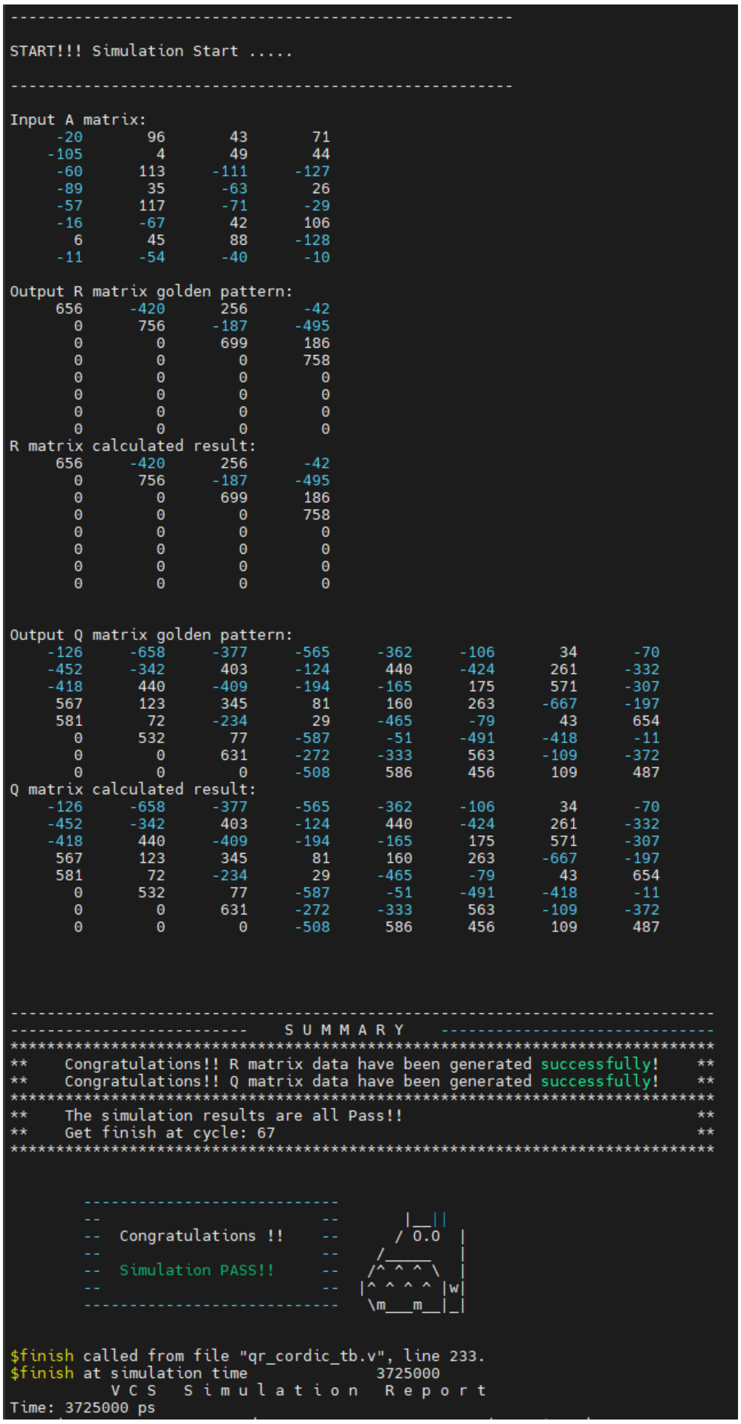
ii. Area report



```
****************************************
Report : area
Design : qr_cordic
Version: U-2022.12
Date   : Fri May 24 00:41:30 2024
****************************************

Library(s) Used:

    slow (File: /home/cell_library/CBDK_IC_Contest_v2.5/SynopsysDC/db/slow.db)

Number of ports:                          164
Number of nets:                         49694
Number of cells:                        44155
Number of combinational cells:          42075
Number of sequential cells:              2080
Number of macros/black boxes:               0
Number of buf/inv:                       6200
Number of references:                     124

Combinational area:             444070.399000
Buf/Inv area:                    27816.990759
Noncombinational area:           67480.134827
Macro/Black Box area:                0.000000
Net Interconnect area:         5437673.880432

Total cell area:                511550.533827
Total area:                    5949224.414259
1
```

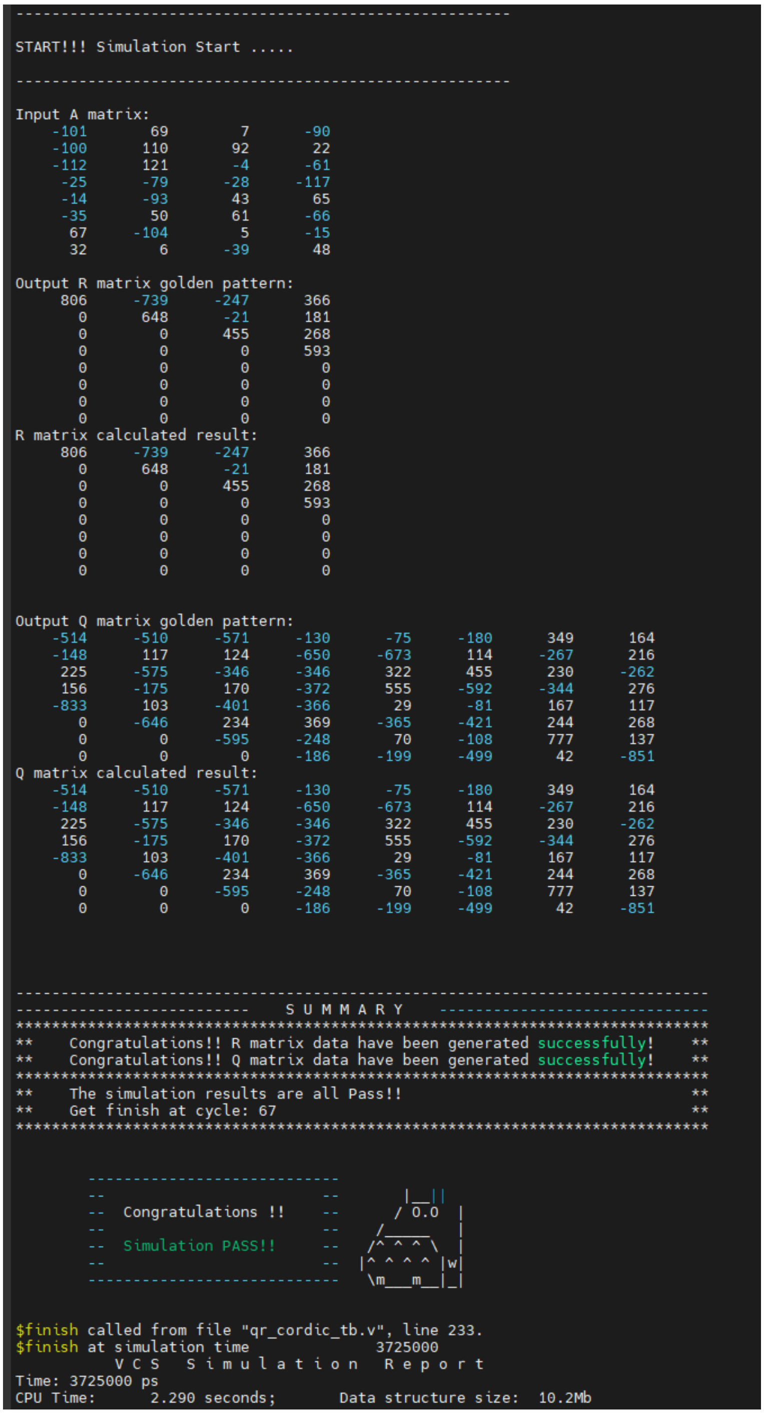
d. Gate-level simulation

Pattern 1:



```
-------------------------------------------------------

START!!! Simulation Start .....

-------------------------------------------------------

Input A matrix:
     -20       96       43       71
    -105        4       49       44
     -60      113     -111     -127
     -89       35      -63       26
     -57      117      -71      -29
     -16      -67       42      106
       6       45       88     -128
     -11      -54      -40      -10

Output R matrix golden pattern:
     656     -420      256      -42
       0      756     -187     -495
       0        0      699      186
       0        0        0      758
       0        0        0        0
       0        0        0        0
       0        0        0        0
       0        0        0        0
R matrix calculated result:
     656     -420      256      -42
       0      756     -187     -495
       0        0      699      186
       0        0        0      758
       0        0        0        0
       0        0        0        0
       0        0        0        0
       0        0        0        0


Output Q matrix golden pattern:
    -126     -658     -377     -565     -362     -106       34      -70
    -452     -342      403     -124      440     -424      261     -332
    -418      440     -409     -194     -165      175      571     -307
     567      123      345       81      160      263     -667     -197
     581       72     -234       29     -465      -79       43      654
       0      532       77     -587      -51     -491     -418      -11
       0        0      631     -272     -333      563     -109     -372
       0        0        0     -508      586      456      109      487
Q matrix calculated result:
    -126     -658     -377     -565     -362     -106       34      -70
    -452     -342      403     -124      440     -424      261     -332
    -418      440     -409     -194     -165      175      571     -307
     567      123      345       81      160      263     -667     -197
     581       72     -234       29     -465      -79       43      654
       0      532       77     -587      -51     -491     -418      -11
       0        0      631     -272     -333      563     -109     -372
       0        0        0     -508      586      456      109      487



-----------------------------------------------------------------------------
--------------------------   S U M M A R Y   --------------------------------
*****************************************************************************
**    Congratulations!! R matrix data have been generated successfully!    **
**    Congratulations!! Q matrix data have been generated successfully!    **
*****************************************************************************
**    The simulation results are all Pass!!                                **
**    Get finish at cycle: 67                                              **
*****************************************************************************


        ---------------------------
        --                       --       |__||
        --  Congratulations !!   --      / 0.0  |
        --                       --     /_____  |
        --  Simulation PASS!!    --    /^ ^ ^ \  |
        --                       --   |^ ^ ^ ^ |w|
        ---------------------------    \m___m__|_|


$finish called from file "qr_cordic_tb.v", line 233.
$finish at simulation time                 3725000
           V C S   S i m u l a t i o n   R e p o r t
Time: 3725000 ps
```

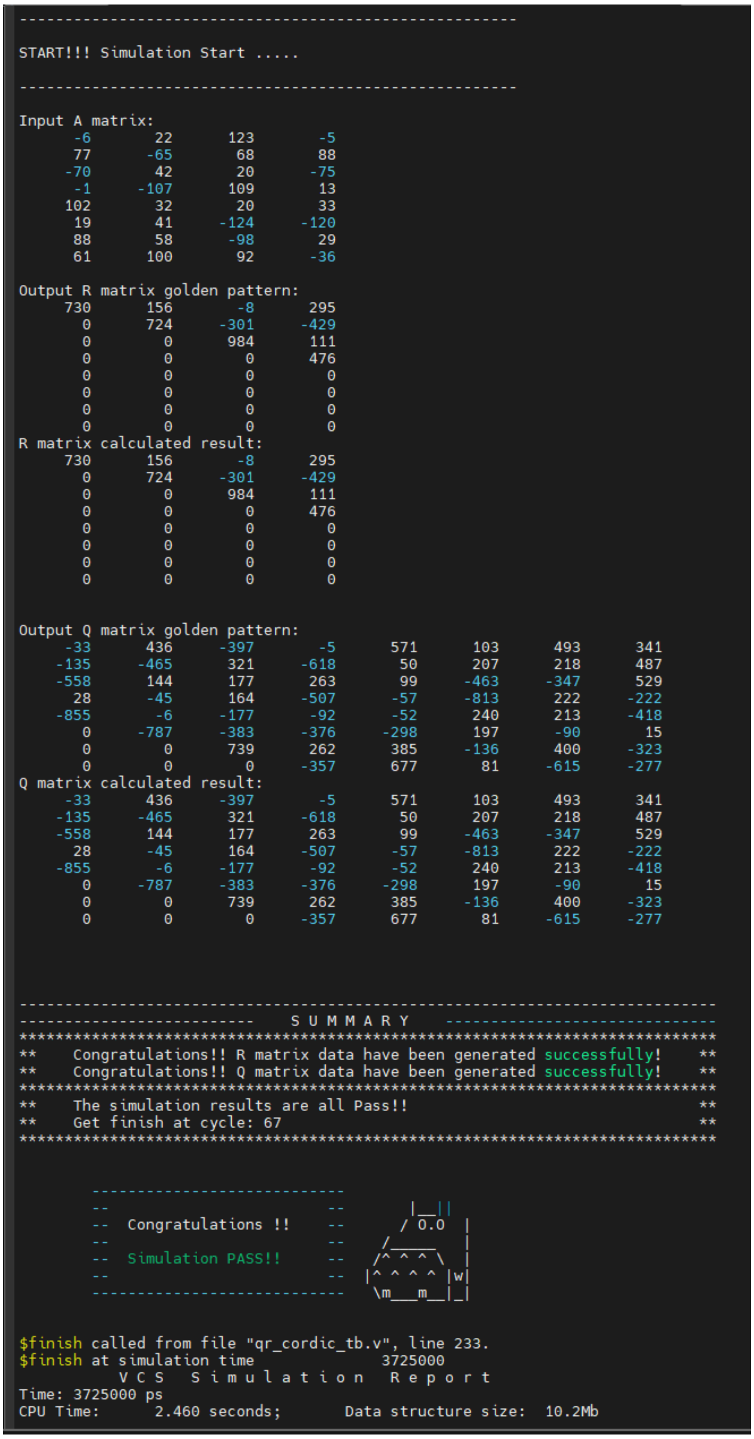
Pattern 2:



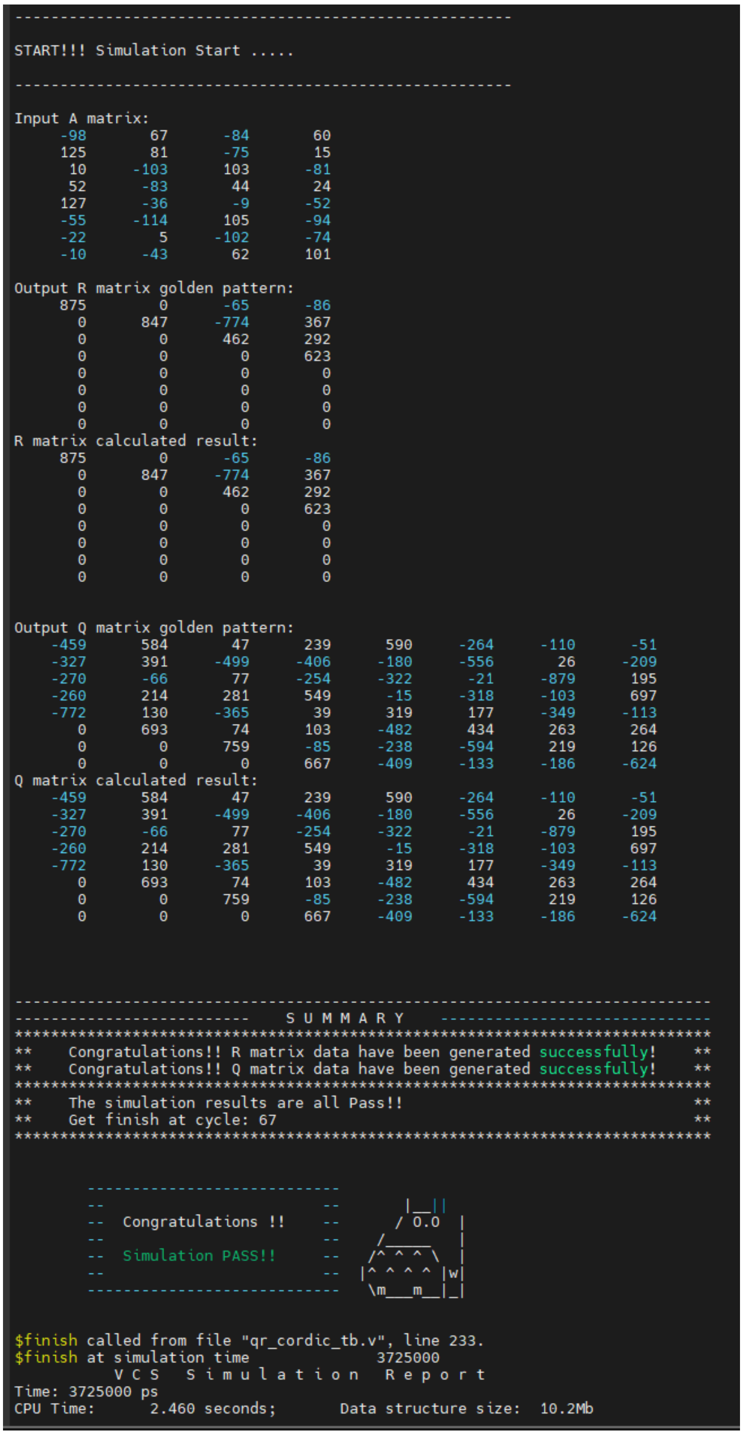
```
-------------------------------------------------------

START!!! Simulation Start .....

-------------------------------------------------------

Input A matrix:
    -101       69        7      -90
    -100      110       92       22
    -112      121       -4      -61
     -25      -79      -28     -117
     -14      -93       43       65
     -35       50       61      -66
      67     -104        5      -15
      32        6      -39       48

Output R matrix golden pattern:
     806     -739     -247      366
       0      648      -21      181
       0        0      455      268
       0        0        0      593
       0        0        0        0
       0        0        0        0
       0        0        0        0
       0        0        0        0
R matrix calculated result:
     806     -739     -247      366
       0      648      -21      181
       0        0      455      268
       0        0        0      593
       0        0        0        0
       0        0        0        0
       0        0        0        0
       0        0        0        0


Output Q matrix golden pattern:
    -514     -510     -571     -130      -75     -180      349      164
    -148      117      124     -650     -673      114     -267      216
     225     -575     -346     -346      322      455      230     -262
     156     -175      170     -372      555     -592     -344      276
    -833      103     -401     -366       29      -81      167      117
       0     -646      234      369     -365     -421      244      268
       0        0     -595     -248       70     -108      777      137
       0        0        0     -186     -199     -499       42     -851
Q matrix calculated result:
    -514     -510     -571     -130      -75     -180      349      164
    -148      117      124     -650     -673      114     -267      216
     225     -575     -346     -346      322      455      230     -262
     156     -175      170     -372      555     -592     -344      276
    -833      103     -401     -366       29      -81      167      117
       0     -646      234      369     -365     -421      244      268
       0        0     -595     -248       70     -108      777      137
       0        0        0     -186     -199     -499       42     -851



-----------------------------------------------------------------------------
--------------------------   S U M M A R Y   --------------------------------
*****************************************************************************
**    Congratulations!! R matrix data have been generated successfully!    **
**    Congratulations!! Q matrix data have been generated successfully!    **
*****************************************************************************
**    The simulation results are all Pass!!                                **
**    Get finish at cycle: 67                                              **
*****************************************************************************


        ---------------------------
        --                       --       |__||
        --  Congratulations !!   --      / 0.0  |
        --                       --     /_____  |
        --  Simulation PASS!!    --    /^ ^ ^ \  |
        --                       --   |^ ^ ^ ^ |w|
        ---------------------------    \m___m__|_|


$finish called from file "qr_cordic_tb.v", line 233.
$finish at simulation time                 3725000
           V C S   S i m u l a t i o n   R e p o r t
Time: 3725000 ps
CPU Time:      2.290 seconds;       Data structure size:   10.2Mb
```

Pattern 3:

Pattern4:



```
----------------------------------------------------

START!!! Simulation Start .....

----------------------------------------------------

Input A matrix:
        -6        22       123        -5
        77       -65        68        88
       -70        42        20       -75
        -1      -107       109        13
       102        32        20        33
        19        41      -124      -120
        88        58       -98        29
        61       100        92       -36

Output R matrix golden pattern:
       730       156        -8       295
         0       724      -301      -429
         0         0       984       111
         0         0         0       476
         0         0         0         0
         0         0         0         0
         0         0         0         0
         0         0         0         0
R matrix calculated result:
       730       156        -8       295
         0       724      -301      -429
         0         0       984       111
         0         0         0       476
         0         0         0         0
         0         0         0         0
         0         0         0         0
         0         0         0         0


Output Q matrix golden pattern:
       -33       436      -397        -5       571       103       493       341
      -135      -465       321      -618        50       207       218       487
      -558       144       177       263        99      -463      -347       529
        28       -45       164      -507       -57      -813       222      -222
      -855        -6      -177       -92       -52       240       213      -418
         0      -787      -383      -376      -298       197       -90        15
         0         0       739       262       385      -136       400      -323
         0         0         0      -357       677        81      -615      -277
Q matrix calculated result:
       -33       436      -397        -5       571       103       493       341
      -135      -465       321      -618        50       207       218       487
      -558       144       177       263        99      -463      -347       529
        28       -45       164      -507       -57      -813       222      -222
      -855        -6      -177       -92       -52       240       213      -418
         0      -787      -383      -376      -298       197       -90        15
         0         0       739       262       385      -136       400      -323
         0         0         0      -357       677        81      -615      -277



-----------------------------------------------------------------------------
--------------------------   S U M M A R Y   --------------------------------
*****************************************************************************
**    Congratulations!! R matrix data have been generated successfully!    **
**    Congratulations!! Q matrix data have been generated successfully!    **
*****************************************************************************
**    The simulation results are all Pass!!                                **
**    Get finish at cycle: 67                                              **
*****************************************************************************


        ----------------------------
        --                        --       |__||
        --  Congratulations !!    --      / O.O  |
        --                        --    /_____   |
        --  Simulation PASS!!     --   /^ ^ ^ \  |
        --                        --  |^ ^ ^ ^ |w|
        ----------------------------   \m___m__|_|


$finish called from file "qr_cordic_tb.v", line 233.
$finish at simulation time              3725000
           V C S   S i m u l a t i o n   R e p o r t
Time: 3725000 ps
CPU Time:      2.460 seconds;       Data structure size:  10.2Mb
```



```
----------------------------------------------------

START!!! Simulation Start .....

----------------------------------------------------

Input A matrix:
       -98        67       -84        60
       125        81       -75        15
        10      -103       103       -81
        52       -83        44        24
       127       -36        -9       -52
       -55      -114       105       -94
       -22         5      -102       -74
       -10       -43        62       101

Output R matrix golden pattern:
       875         0       -65       -86
         0       847      -774       367
         0         0       462       292
         0         0         0       623
         0         0         0         0
         0         0         0         0
         0         0         0         0
         0         0         0         0
R matrix calculated result:
       875         0       -65       -86
         0       847      -774       367
         0         0       462       292
         0         0         0       623
         0         0         0         0
         0         0         0         0
         0         0         0         0
         0         0         0         0


Output Q matrix golden pattern:
      -459       584        47       239       590      -264      -110       -51
      -327       391      -499      -406      -180      -556        26      -209
      -270       -66        77      -254      -322       -21      -879       195
      -260       214       281       549       -15      -318      -103       697
      -772       130      -365        39       319       177      -349      -113
         0       693        74       103      -482       434       263       264
         0         0       759       -85      -238      -594       219       126
         0         0         0       667      -409      -133      -186      -624
Q matrix calculated result:
      -459       584        47       239       590      -264      -110       -51
      -327       391      -499      -406      -180      -556        26      -209
      -270       -66        77      -254      -322       -21      -879       195
      -260       214       281       549       -15      -318      -103       697
      -772       130      -365        39       319       177      -349      -113
         0       693        74       103      -482       434       263       264
         0         0       759       -85      -238      -594       219       126
         0         0         0       667      -409      -133      -186      -624



-----------------------------------------------------------------------------
--------------------------   S U M M A R Y   --------------------------------
*****************************************************************************
**    Congratulations!! R matrix data have been generated successfully!    **
**    Congratulations!! Q matrix data have been generated successfully!    **
*****************************************************************************
**    The simulation results are all Pass!!                                **
**    Get finish at cycle: 67                                              **
*****************************************************************************


        ----------------------------
        --                        --       |__||
        --  Congratulations !!    --      / O.O  |
        --                        --    /_____   |
        --  Simulation PASS!!     --   /^ ^ ^ \  |
        --                        --  |^ ^ ^ ^ |w|
        ----------------------------   \m___m__|_|


$finish called from file "qr_cordic_tb.v", line 233.
$finish at simulation time              3725000
           V C S   S i m u l a t i o n   R e p o r t
Time: 3725000 ps
CPU Time:      2.460 seconds;       Data structure size:  10.2Mb
```