# OpenCPI
# Tutorial 7hw: Using HDL Primitive Libraries

*OpenCPI Release: v2.4.7*

*Revision History*

| Revision | Description of Change | Date |
|---|---|---|
| 1.0 | Creation from Lab 7 developed by BIA | 2019-10-01 |
| 2.4 | Update for release 2.4.0 | 2022-01-20 |
| 2.4.1 | Update for patch release 2.4.1 | 2022-02-11 |
| 2.4.3 | Update GUI and CLI to reflect changes in ocpidev | 2022-08-24 |

## Table of Contents

# 1 Overview

**Note:** This tutorial demonstrates the same steps as Tutorial 7, but it includes a hardware platform in the demonstration; in this case, it is the ADALM-PLUTO device (In OpenCPI, this is the **`plutosdr`** HDL platform).

This tutorial introduces you to HDL primitives and primitive libraries. ***HDL primitives*** are HDL assets that are lower level than workers. They can be used as building blocks for workers and are useful for HDL workers when there is lower-level code that is reused or shared in different workers. Using HDL primitives is also useful when there are non-OpenCPI code modules that are imported and need to be left untouched so that they remain useful outside of OpenCPI.

HDL primitives are the preferred way in OpenCPI to store and present reusable HDL for use in multiple workers. Using HDL primitives is not required, but it is recommended practice.

HDL primitives can be libraries or cores. An HDL primitive library is a collection of modules compiled from source code that can be referenced in HDL worker code, while an HDL primitive core is a single module. This tutorial demonstrates how to create an HDL primitive library and use it in HDL worker code. Our example is the Automatic Gain Control (AGC) Complex component (**`agc_complex`**) in the **`ocpi.tutorial`** project. This component inputs complex signed samples, drives the amplitude of both I and Q input rails to a reference level, and outputs complex signed samples.

The response time and output level of the circuit are programmable, as is the ability to update/hold the gain differential used in the feedback loop. The size of the averaging window used for peak detection is build-time programmable using the **`avg_window`** parameter, which is recommended to be a power-of-two to enable hardware division implementation with shift registers.

The **`ref`** property controls the desired output amplitude, while the **`mu`** property controls the AGC time constant, thus determining the response time of the circuit.

This implementation uses three multipliers per I/Q rail to process input data at the clock rate; that is, this worker can handle a new input value every clock cycle. This circuit produces output one clock cycle after each valid input, but the input-to-output latency is actually three valid clock cycles.

The AGC Complex worker uses the OpenCPI **`iqstream_protocol`** for both input and output ports (see **`$OCPI_ROOT_DIR/projects/core/specs/iqstream_protocol.xml`**). This protocol defines an interface of 16-bit complex signed samples. The **`data_width`** "parameter" property for the HDL worker can be used to reduce the worker's internal data width to less than 16 bits.

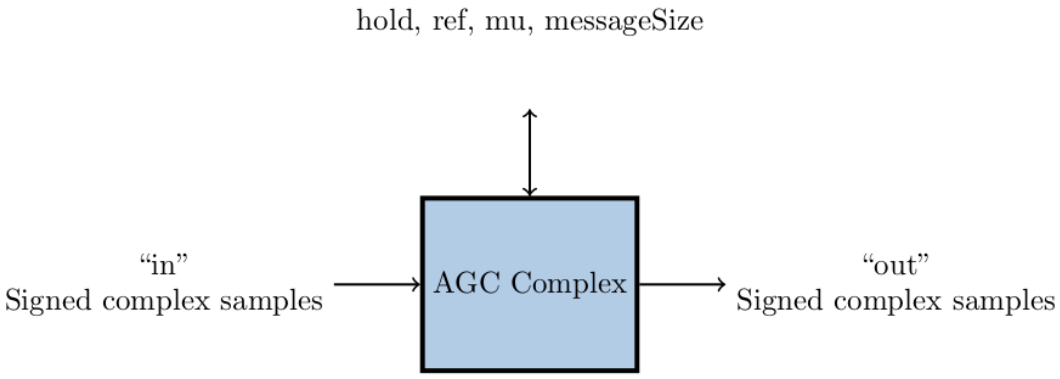



*Figure 1: AGC Complex Component Function*

### 1.1 Tutorial Objectives

The purpose of this tutorial is to demonstrate how to create an HDL primitive library and use it in an HDL worker. It shows you how to:

- Create the HDL primitive library to be used by the AGC complex worker.
- Create the AGC complex component, HDL worker, and component unit test suite (aka “unit test”) and build the worker and unit test for the **`xsim`** and **`plutosdr`** platforms.
- Run the component unit test suite on the **`xsim`** and **`plutosdr`** platforms and view the generated output.

The provided source files show:

- A primitive library package declaration file that enables VHDL code to instantiate all entities and modules in the primitive library.
- A primitive library VHDL source file that implements a simple automatic gain control (AGC) with two independent channels for I and Q respectively. This file in particular stores the record signal names.

**Note**: This part of the tutorial requires a machine with HDL platform support for the ADALM-PLUTO hardware device (HDL platform **`plutosdr`**). Details of how to set up and configure the platform are beyond the scope of this tutorial.

### *1.2 What's Provided for This Tutorial*

The built-in OpenCPI tutorial project **`ocpi.tutorial`** provides source code for the following items in this tutorial:

- The HDL primitive source and package declaration VHDL files, in **`hdl/prims/agc.vhd`** and **`hdl/prims/prims_pkg.vhd`**
- The VHDL source code for the **`agc_complex`** worker, in **`components/agc_complex.hdl/agc_complex.vhd`**
- The unit test scripts **`generate.py`** and **`verify.py`**, written in Python
- The unit test **`bash`** shell script **`view.sh`**

The **`ocpi.tutorial`** project also provides the XML source for all of the assets used to build and run the example component, worker and tests.

Instructions for copying these items from the **`ocpi.tutorial`** project into the "demo" tutorial project are provided in the relevant sections of this document. The source code for these items is also available as text in the relevant sections of this document that you can copy and paste into the relevant files following the instructions given in the section.

**Note:** when copying and pasting text from this document, be sure to remove any line breaks in code or command lines. The backslash character (\) is used in command lines (where feasible) to indicate a line break.

### *1.3 Prerequisites to Using This Tutorial*

This tutorial (Tutorial 7hw) has the system prerequisites described in ***OpenCPI Tutorial 1: Component-based Development***. See the prerequisites section in Tutorial 1 for details. In addition to these requirements, this tutorial uses the **`plutosdr`** platform, and so the corresponding OSP should be downloaded and installed. See the section "Installation Steps for Platforms" in the ***OpenCPI Installation Guide***.

Before you begin this tutorial, you should have successfully completed Tutorials 1-6.

We recommend reading the following briefings and guides before getting started with this tutorial:

- Briefing 9 HDL Assemblies. This briefing introduces HDL assembly concepts and terminology.
- Briefing 10 HDL Primitives. This briefing introduces HDL primitives concepts and terminology.
- The "HDL Primitives" section in the ***OpenCPI HDL Development Guide***.

### *1.4 Documentation References*

The documents listed in the following table provide detailed information about subjects discussed in this tutorial. The documents listed here are not required reading for this tutorial but will likely be of interest for more in-depth learning.

*Table 1 - OpenCPI Reference Documentation*

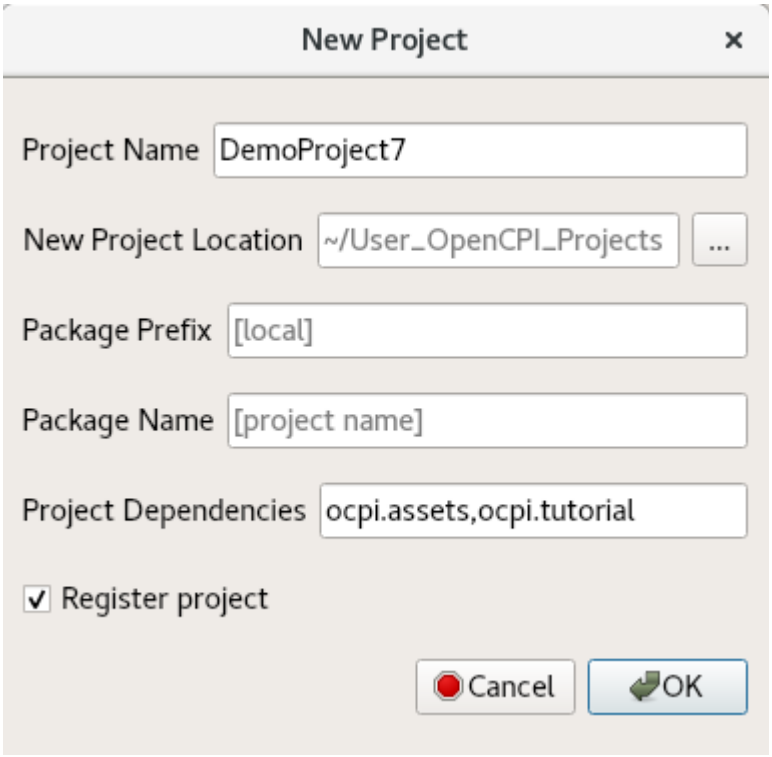
| Title | Published By | Public URL |
|---|---|---|
| OpenCPI User Guide | OpenCPI | https://opencpi.gitlab.io/releases/v2.4.7/docs/OpenCPI_User.pdf |
| OpenCPI Application Development Guide | OpenCPI | https://opencpi.gitlab.io/releases/v2.4.7/docs/OpenCPI_Application_Development_Guide.pdf |
| OpenCPI Component Development Guide | OpenCPI | https://opencpi.gitlab.io/releases/v2.4.7/docs/OpenCPI_Component_Development_Guide.pdf |
| OpenCPI HDL Development Guide | OpenCPI | https://opencpi.gitlab.io/releases/v2.4.7/docs/OpenCPI_HDL_Development_Guide.pdf |
| OpenCPI RCC Development Guide | OpenCPI | https://opencpi.gitlab.io/releases/v2.4.7/docs/OpenCPI_RCC_Development_Guide.pdf |

## 2 Create New Project

We'll create a new, clean project for this tutorial; we'll call it **`DemoProject7`**.

To create the project using the OpenCPI GUI:

- From the GUI menu bar at the top of the window, select **Create** > **Project.**
- The **New Project** dialog is displayed. In **Project Name**, enter **DemoProject7.**
- In **Project Dependencies**, enter **ocpi.assets,ocpi.tutorial**.
- Check **Register project**.
- Click **OK**. When the operation finishes, you'll see the **`DemoProject7`** project directory as well as a some other generated files.




To create the new project from the command line, use the following **`ocpidev`** command:

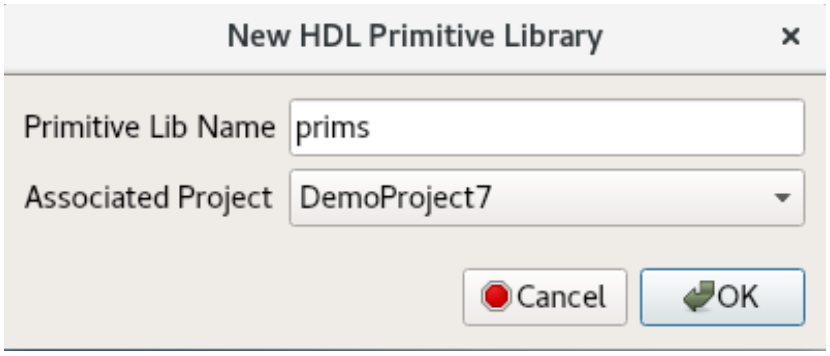
```
ocpidev -D ocpi.assets -D ocpi.tutorial create project DemoProject7
--register
```

## 3 Create HDL Primitive Library

You must now create and build the HDL primitive library.

To create the project using the OpenCPI GUI:

- From the GUI menu bar at the top of the window, select **Create** > **HDL** >**Primitive Library**.
- The **New HDL Primitive Library** dialog is displayed. In **Primitive Lib Name**, enter **prims**.
- From the **Associated Project** drop-down list, select **DemoProject7**.
- Click **OK**.




To create the primitive library from the command line, use the following **`ocpidev`** command from the **`DemoProject7/`** directory:

```
ocpidev create hdl primitive library prims
```

## 4 Copy HDL Primitive Library Files from the Tutorial Project

Next, we need to copy the provided primitive source file **agc.vhd** and primitive package **prims_pkg.vhd** from the **ocpi.tutorial** project directly into the primitive library. Navigate to the **hdl/primitives/prims/** subdirectory in **DemoProject7** and then use the commands:

```
cp
$OCPI_ROOT_DIR/projects/tutorial/hdl/primitives/prims/
agc.vhd .
cp
$OCPI_ROOT_DIR/projects/tutorial/hdl/primitives/prims/
prims_pkg.vhd .
```

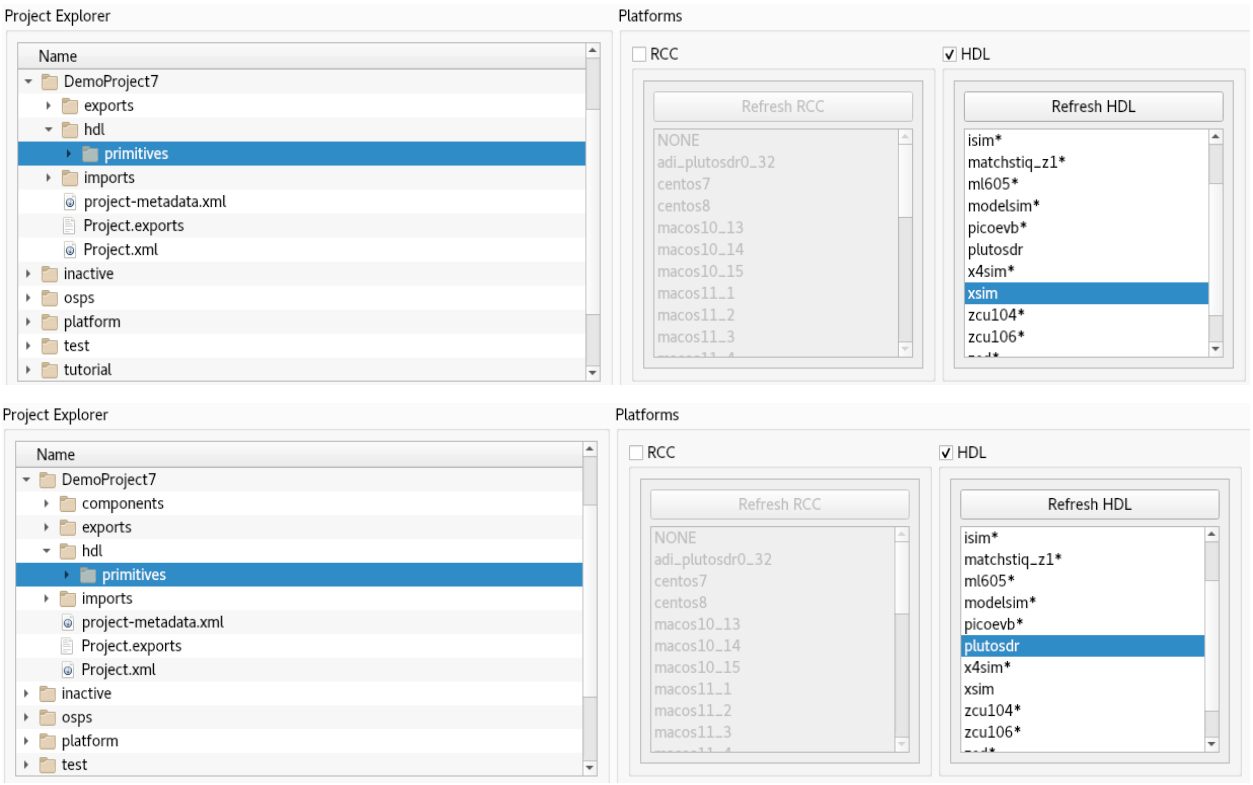
Now that you've copied the files, you can open and examine the contents. You'll see that **agc.vhd** implements the AGC component logic and that **prims.pkg.vhd** enables the primitive source code to be callable by HDL workers.

# 5 Build HDL Primitive Library

Now we'll build the HDL primitive library we just copied from the tutorial project for the target HDL platforms (**`xsim`** and **`plutosdr`**).

To build from the OpenCPI GUI:

- In the Platforms panel, check **HDL,** select **xsim** and uncheck **RCC**. Once the build finishes, come back to this step but select **plutosdr** instead.
- In the Project Explorer panel, select **primitives.**
- Right-click **primitives** and then select **Build**.




To build from the command line, first build the primitive library for the **`xsim`** HDL platform by running the following **`ocpidev`** command from **`DemoProject7/hdl/primitives/`**:

```
ocpidev build --hdl-platform xsim
```

Next, build the primitive library for the **`plutosdr`** HDL platform with the **`ocpidev`** command:

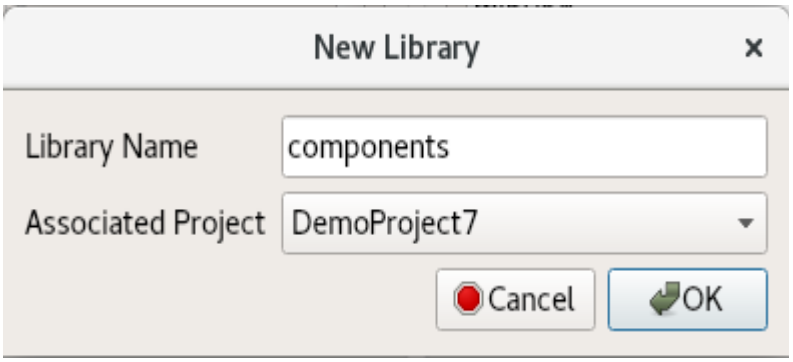
```
ocpidev build --hdl-platform plutosdr
```

## 6 Create Component Library

Before we can create our component, we need to create a component library for it.

To create the **`components`** library in the OpenCPI GUI:

- From the GUI menu bar at the top of the window, select **Create** > **Component Library**.
- The **New Library** dialog is displayed. In **Library Name**, enter **components**.
- From the **Associated Project** drop-down list, select **DemoProject7**.




- Click **OK**.

To create the **`components`** library with **`ocpidev`**, run the following command in the **`DemoProject7/`** directory:

```
ocpidev create library components
```

You should now see a **`lib/`** directory and a **`components.xml`** file in the **components/** directory. We need to edit the **`components.xml`** file. Using a text editor, open and edit **`components/components.xml`** so that it has the following content:

```
<library
  HdlLibraries='prims'
/>
```

# 7 Create Component

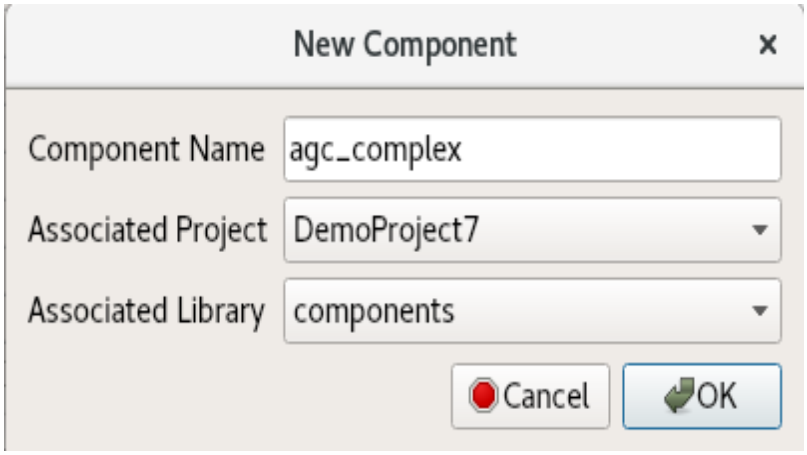
Now we need to create the OCS (OpenCPI Component Specification) for **`agc_complex`** that defines its properties and ports.

### 7.1 Create Component Spec

We'll create our **`agc_complex`** component spec in the **`components`** library we just created.

To create the component in the OpenCPI GUI:

- From the GUI menu bar at the top of the window, select **Create** > **Component Spec**.
- The **New Component** dialog is displayed. In **Component Name**, enter **agc_complex**.
- Select **DemoProject7** from the **Associated Project** drop-down list.
- The **Associated Library** field will auto-set to **components**.




- Click **OK**.

To create the component spec with **`ocpidev`**, run the following command in the **`DemoProject7/components/`** directory:

```
ocpidev create component agc_complex
```

### 7.2 Add Component Properties and Ports

The previous command created the component spec **`agc_complex-spec.xml`** in **`components/agc_complex.comp/`**. We must now add properties and ports to the component spec.

To do so, we'll simply copy the reference spec **agc_complex-spec.xml** directly from **ocpi.tutorial** into our **DemoProject7/components/agc_complex.comp/** directory:

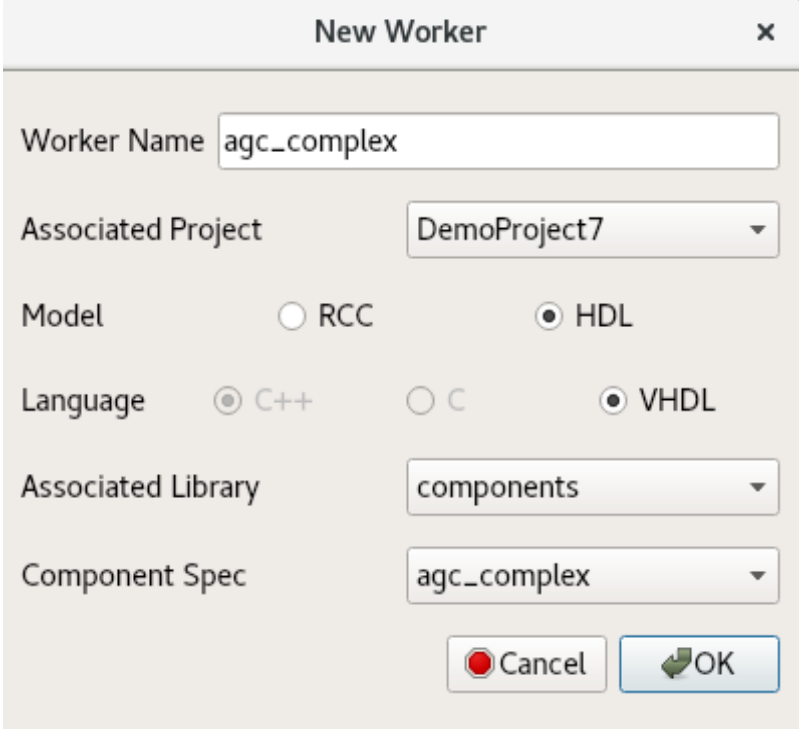
```
# cd to the agc_complex.comp/ directory in DemoProject7
cd DemoProject7/components/agc_complex.comp/


cp
$OCPI_ROOT_DIR/projects/tutorial/components/specs/agc_complex-
spec.xml .
```

## 8 Create Worker

We will now create the HDL worker.

To create the worker in the OpenCPI GUI:

- From the GUI menu bar at the top of the window, select **Create** > **Worker**.
- The **New Worker** dialog is displayed. In **Worker Name**, enter **agc_complex**.
- From the **Associated Project** drop-down list, select **DemoProject7**.
- For **Model**, select **HDL**. **Language** should then automatically select **VHDL**.
- From the **Associated Library** drop-down list, confirm **components** is selected.
- From the **Component Spec** drop-down list, select **agc_complex**.




- Click **OK**.

To create the worker with **ocpidev**, run the following command in the **DemoProject7/components/** directory:

```
ocpidev create worker agc_complex.hdl
```

### 8.1 Update HDL Worker Skeleton Files

We will now populate the skeleton files in the previously-generated **agc_complex.hdl/** directory with reference files from the tutorial project.

Use the following commands to copy the files for **agc_complex.vhd** and **agc_complex.xml** from the **ocpi.tutorial** project:

```
# cd to the agc_complex.hdl/ directory in DemoProject7
cd components/agc_complex.hdl/
cp
$OCPI_ROOT_DIR/projects/tutorial/components/agc_complex.hdl/
agc_complex.vhd .
cp
$OCPI_ROOT_DIR/projects/tutorial/components/agc_complex.hdl/
agc_complex.xml .
```

You can examine these files for more context. The **agc_complex.vhd** file in particular holds good information to look into as it has an explanation of the agc circuit. This file allows the worker to function properly.

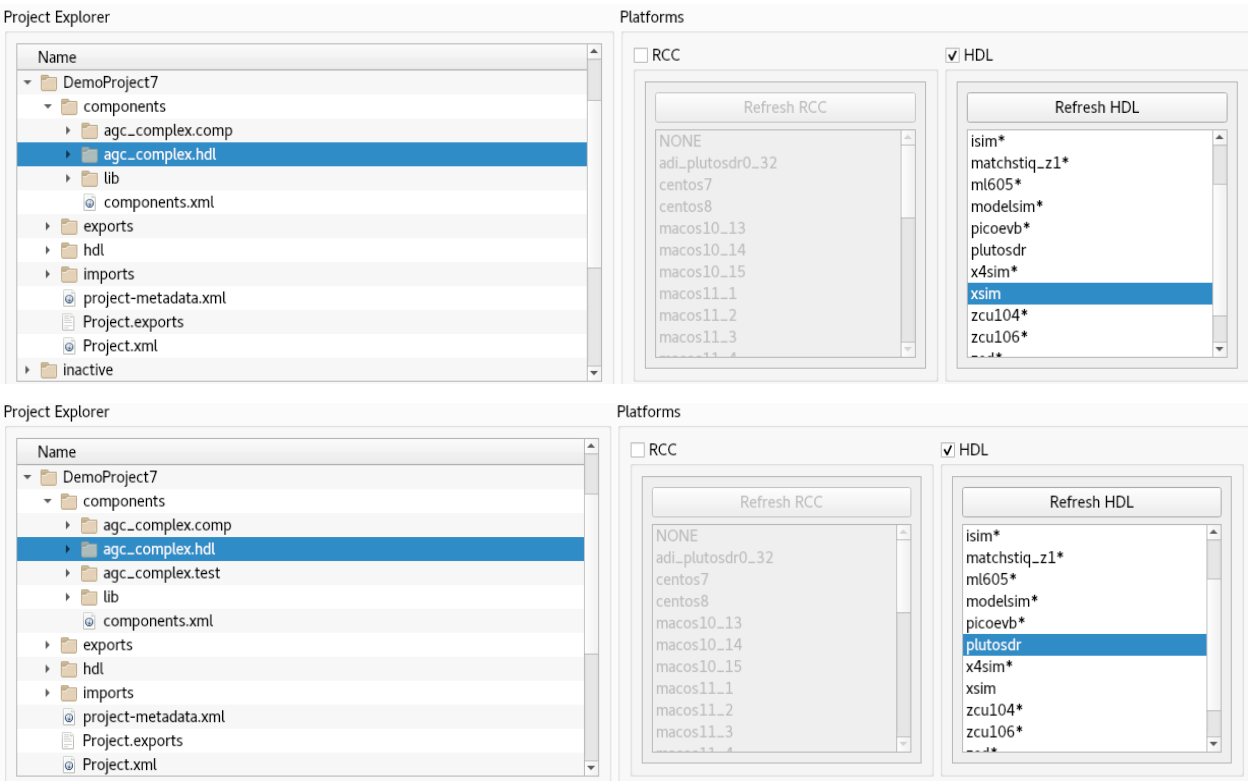
In **agc_complex.hdl/gen/**, you'll see an assortment of files that do not need to be edited. They are automatically generated when the worker has been created, and if they are removed will be recreated when the **ocpidev build** command is invoked.

## 8.2 Build Worker

If all goes well, we can now build the worker from the **`components/agc_complex.hdl/`** directory.

To build from the OpenCPI GUI:

- In the Platforms panel, check **HDL**. select **xsim**, and uncheck **RCC**. After this builds, repeat these steps but with **plutosdr** selected.
- In the Project Explorer panel, select **components.**
- Right-click **agc_complex.hdl** and then select **Build**.




To build the worker for **`xsim`** from the command line, run the following **`ocpidev`** command in the **`components/agc_complex.hdl/`** directory in **`DemoProject7`**:

```
ocpidev build --hdl-platform xsim
```

Next, build the worker for **`plutosdr`** with the **`ocpidev`** command:

```
ocpidev build --hdl-platform plutosdr
```

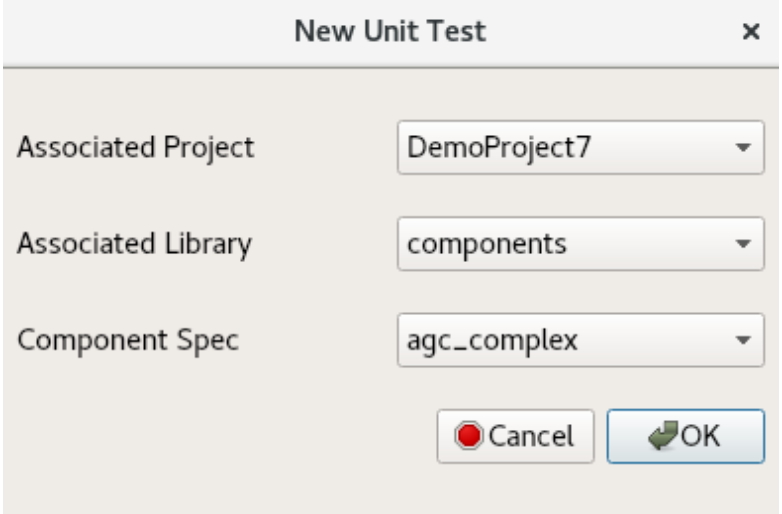
Navigate to **`components/agc_complex.hdl/`**. There should be two new subdirectories **`target-<platform>`** - one for **`xsim`** (**`target-xsim`**) and one for **`plutosdr`** (**`target-zynq`**) that contain the artifacts needed to run the worker on these platforms.

# 9 Create Unit Test

Now we'll generate an OpenCPI component test suite (aka "unit test") for our **`agc_complex`** worker.

To create the unit test in the OpenCPI GUI:

- From the GUI menu bar at the top of the window, select **Create** > **Component Test Suite**.
- The **New Unit Test** dialog displayed. From the **Associated Project** drop-down list, select **DemoProject7**.
- From the **Associated Library** drop-down list, confirm **components** is selected.
- From the drop-down list in **Component Spec**, select **agc_complex**.




- Click **OK**.

To create the unit test from the command line, run the following **`ocpidev`** command from the **`DemoProject7/components/`** directory:

```
ocpidev create test agc_complex
```

Now run the **`tree`** command to observe the files created:

```
agc_complex.test
├── generate.py
├── agc_complex-test.xml
├── verify.py
└── view.sh
```

The files of interest here are:

- **`agc_complex-test.xml`**. This is the OpenCPI Test Suite Description (OTSD) XML file. It specifies the test cases and the defaults that apply to all test cases.

- **`generate.py`.** This is a stub file for an optional script that you can create to generate input test data for ports or property value files. There is one script for each input port.
- **`verify.py`**. This is a stub file for an optional script that you can create to verify output test data produced by output ports. There is one script for each output port..
- **`view.sh`**. This is a stub file for an optional script that you can create to view the results of a test execution; for example, a plot. This script may not be necessary or appropriate for many workers. It can work as a helpful aid in the development process, but it is not meant for long-term testing and re-testing.

We want to use the generate, verify and view scripts in this tutorial, so we'll need to edit the OTSD file to specify them and create the code for each script. The next sections describe these steps.

### 9.1 Copy OpenCPI Test Suite Description File

We now have a skeleton **`agc_complex-test.xml`** file that we need to fill out. To do this, we'll simply copy the reference OTSD XML file from the tutorial project with the command:

```
# cd to test suite (aka unit test) directory in DemoProject7
cd components/agc_complex.test/
cp
$OCPI_ROOT_DIR/projects/tutorial/components/agc_complex.test/
agc_complex-test.xml .
```

### *9.2 Copy Unit Test Scripts from Tutorial Project*

Now we need to create code for the empty **`generate.py`**, **`verify.py`** and **`view.sh`** scripts we created when we created the unit test. To do this, we'll simply copy the unit test scripts provided in the tutorial project into our **`DemoProject7`** unit test directory.

#### *9.2.1 Copy generate.py and verify.py Files*

We will simply use the reference files for these items from **`ocpi.tutorial`**. The commands to copy the files into our existing project are shown below:

```
# cd to test suite directory in DemoProject7
cd components/agc_complex.test/
cp
$OCPI_ROOT_DIR/projects/tutorial/components/agc_complex.test/
generate.py .
cp
$OCPI_ROOT_DIR/projects/tutorial/components/agc_complex.test/
verify.py .
```

#### *9.2.2 Edit view.sh Script*

Now open the **`view.sh`** script with a text editor and then copy and paste the following lines at the end of the file (highlighted in red):

```
#!/bin/bash --noprofile
# Use this script to view your input and output data.
# Args: <list-of-user-defined-args> <input-file> <output-file>
$OCPI_ROOT_DIR/projects/tutorial/scripts/plotAndFft.py $2 complex
32768 100&
$OCPI_ROOT_DIR/projects/tutorial/scripts/plotAndFft.py $1 complex
32768 100&
```

**Note:** Make sure your test scripts have read and execute permissions before using them to build and run the **`agc_complex`** unit test. For example, in the **`agc_complex.test/`** directory:

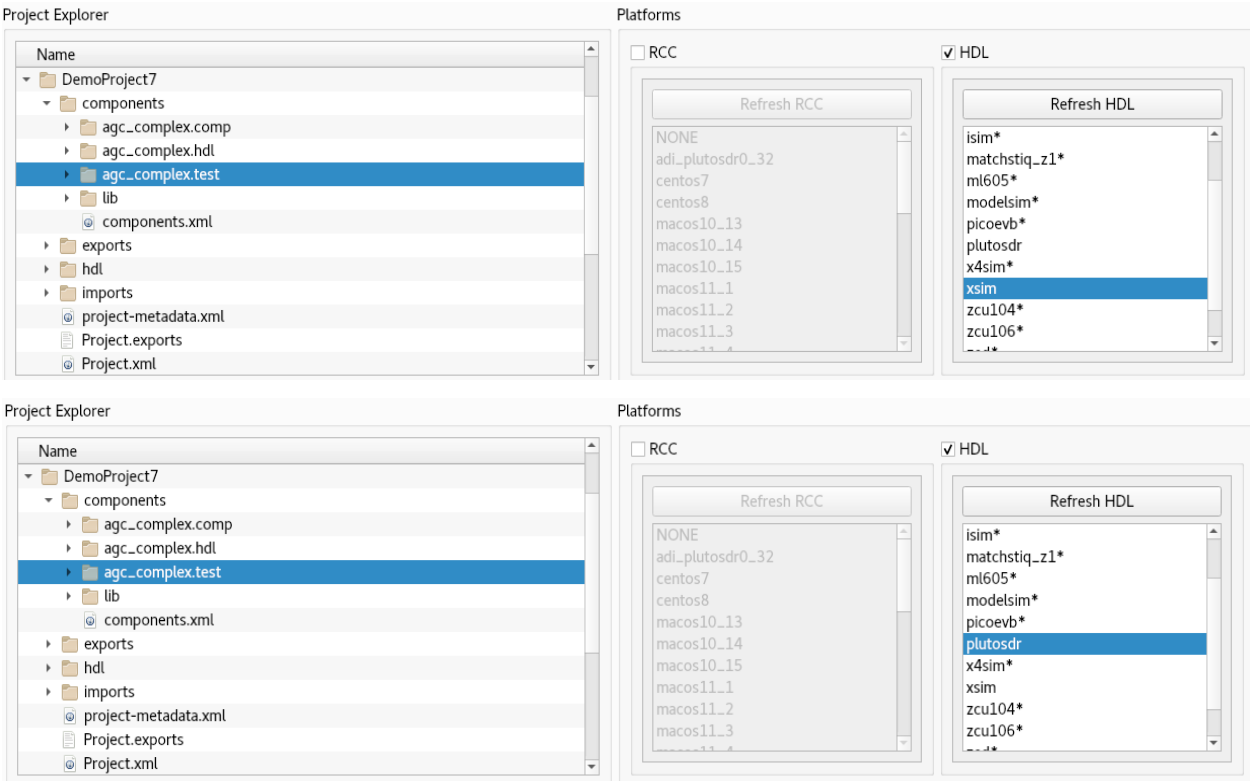
```
chmod 755 generate.py
chmod 755 verify.py
chmod 755 view.sh
```

### *9.3 Build Unit Test*

Now we'll build the unit test for the target platforms.

To build from the OpenCPI GUI:

- In the Platforms panel, check **HDL,** select **xsim**, and uncheck the **RCC** box. After this builds, repeat these steps but with **plutosdr** selected.
- In the Project Explorer panel, select **components.**
- Right-click **agc_complex.test** and select **Build**.




To generate and build the unit test for the **`xsim`** HDL platform from the command line, run the following **`ocpidev`** command from the **`components/agc_complex.test/`** directory:

```
ocpidev build --hdl-platform xsim
```

To generate and build the unit test for the **`plutosdr`** HDL platform from the command line, run the **`ocpidev`** command from the **`components/agc_complex.test/`** directory:

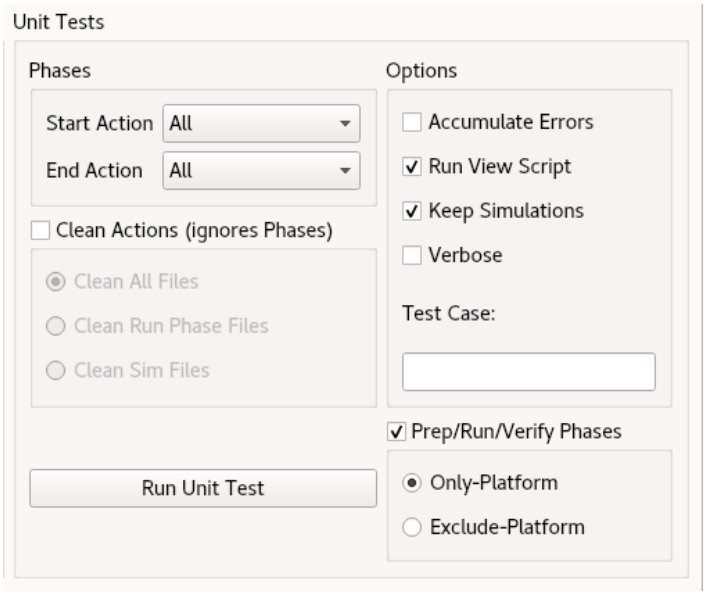
```
ocpidev build --hdl-platform plutosdr
```

## 10 Run Unit Test (XSIM)

We will now run the unit test in **`components/agc_complex.test/`**on the **`xsim`** HDL platform.

To run the unit test with the OpenCPI GUI:

- In the Platforms panel, check **HDL,** select **xsim**, and uncheck the **RCC** box.
- In the Project Explorer panel, select **components.**
- Select **agc_complex.test**.
- In the Unit Tests panel, under Phases, leave **Start Action** and **End Action** set to **All**.
- In the Unit Tests panel, under Options, check **Run View Script** and **Keep Simulations**.
- Under Options, check **Prep/Run/Verify Phases**.
- The greyed-out options below will now be available. Click **Only-Platform.**
- Now click **Run Unit Test**.

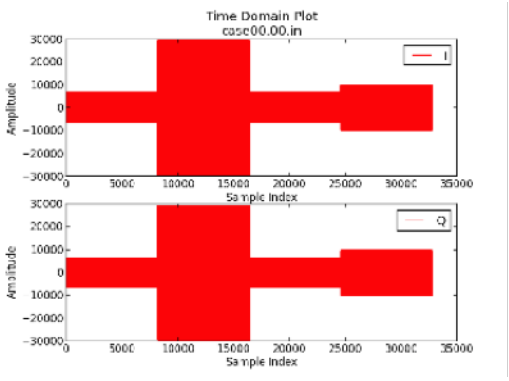


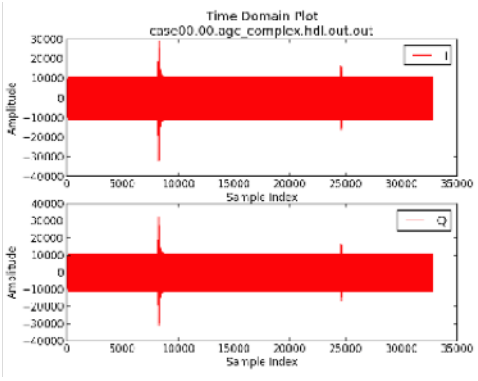

To run the unit test from the command line, use the following **`ocpidev`** command from the **`components/agc_complex.test/`** directory:

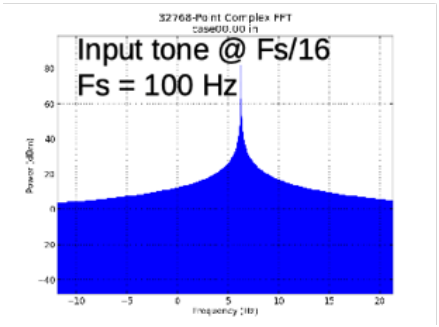
```
ocpidev run --mode all --only-platform xsim --keep-simulations  \
--view
```

## 11 View Unit I/O Test Plots (XSIM)

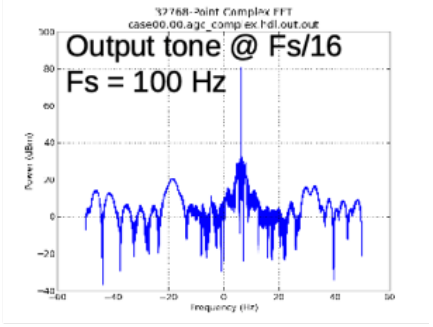
The following figures show the output:




ref = 0x1B26
mu = 0x144E



## 12 View Simulation Waveforms (XSIM)

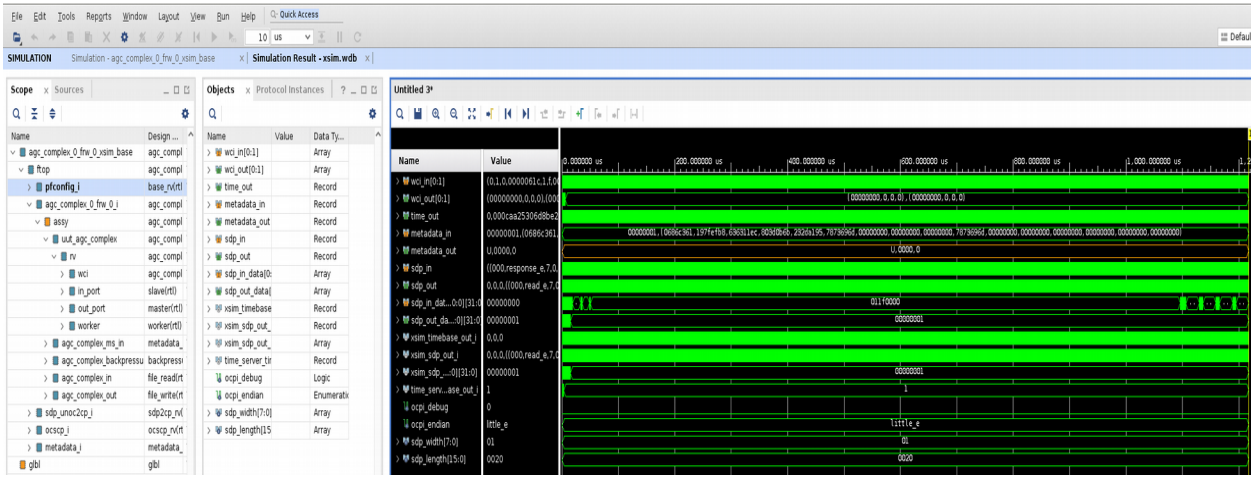
**Note**: In order to view simulation waveforms, you must have checked "keep simulations" in the OpenCPI GUI or have used the **`--keep-simulations`** option on the **`ocpidev`** command line.

In a terminal window, browse to **`agc_complex.test/`** and execute the following command:

```
ocpiview run/xsim/case00.00.agc_complex.hdl.simulation/ &
```

You'll want to expand **`agc_complex_0_frw_0_xsim_base`** by using the arrow to the left and then right-clicking **`pfconfig_i.`** Click on **Add to Wave Window**. For more information on using **`ocpiview`**, see the section "Navigating the Simulator" in Tutorial 6.

You should see the following output:



## 13 Run Unit Test (ADALM-PLUTO)

First we'll check that the ADALM-PLUTO device is connected.

**Note:** Details of how to set up and configure this platform are beyond the scope of this tutorial. See the section "Installation Steps for Platforms" in the ***OpenCPI Installation Guide*** for information about downloading and installing the corresponding OSP.

```
export OCPI_SERVER_ADDRESSES=<Pluto_IP>:12345
ocpiremote status -p analog
```

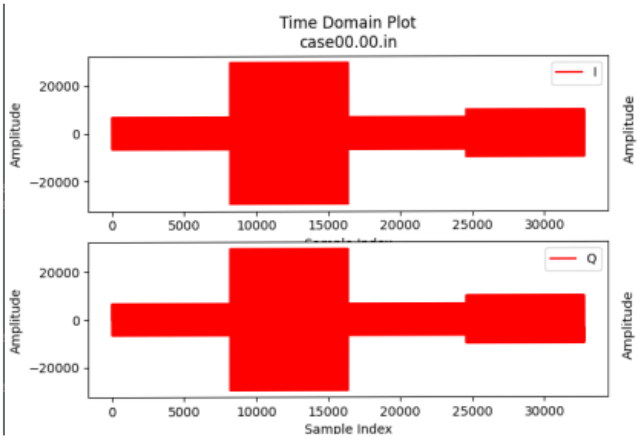
The output should be something similar to:

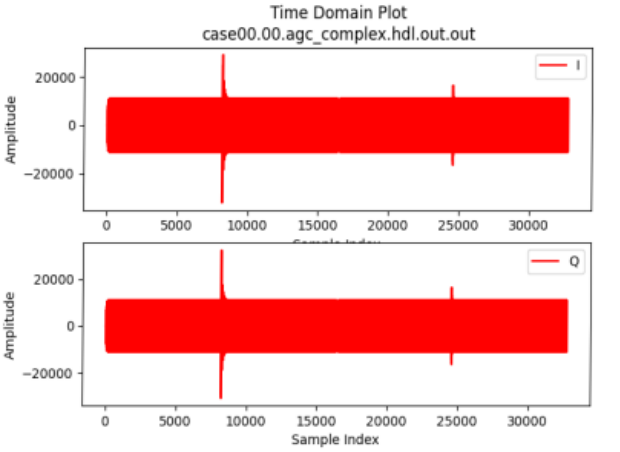
```
Executing remote configuration command: status
Server is running with port: 12345 and pid: 26224
```

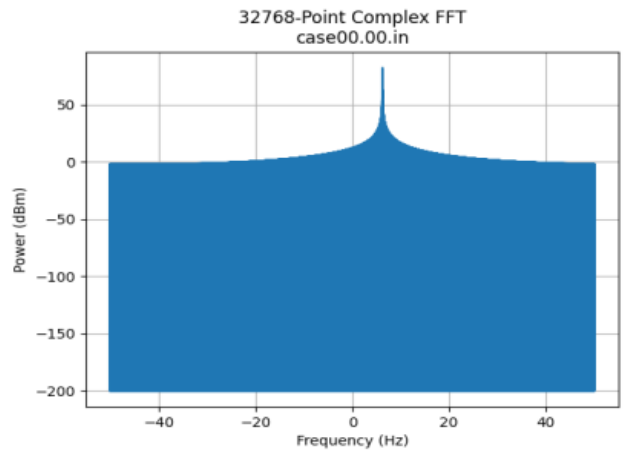
Now we can run the unit test on the **plutosdr** HDL platform and view the results. From the command line in the **DemoProject7/components/agc_complex.test** directory, run the following **ocpidev** command:

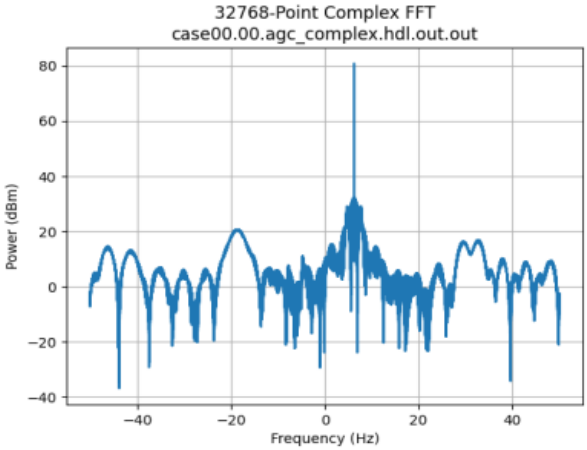
```
ocpidev run --mode all --only-platform plutosdr  \
--keep-simulations --view
```

The output should be identical to that of the simulator output. The main difference is that you should see that the test runs faster on hardware.


Time Domain Plot
case00.00.in
I
Q
Amplitude
Sample Index


Time Domain Plot
case00.00.agc_complex.hdl.out.out
I
Q
Amplitude
Sample Index


32768-Point Complex FFT
case00.00.in
Power (dBm)
Frequency (Hz)


32768-Point Complex FFT
case00.00.agc_complex.hdl.out.out
Power (dBm)
Frequency (Hz)

## 14 Tutorial Summary

Now that you've completed this tutorial, you should be familiar with the basic concepts of HDL primitives and how they are used to store and present reusable HDL. In other existing OpenCPI projects, you should also be able to see how the primitive library is used for multiple workers instead of just the one shown in this tutorial. You can now move on to Tutorial 8 (or Tutorial 8hw), which demonstrates how to use third-party primitive cores in HDL application workers.