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Simple Student-Built IQ Modulator/Demodulators for Wireless Communication Laboratory Digital Communication Link Demonstrations

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ABSTRACT

Instrumentation Vector Signal Generators (VSG) and Vector Signal Analyzers (VSA) are great tools to demonstrate wireless communication link characteristics but are often too expensive for equipping every station in a digital communications laboratory. Software Defined Radios (SDR) equipment are also great tools for demonstrating wireless links as there are models now that are relatively inexpensive and have great performance. The laboratory exercise discussed in this contribution provides many of the learning outcomes possible with VSA/VSG equipment with additional insights at the hardware level that might not be evident using SDRs.

The laboratory exercise in this contribution centers on having students build IQ modulators/demodulators that can be used to demonstrate digital communication links. The required construction parts include semi-rigid coaxial cable, surface mount frequency mixers, and surface mount resistors that cost $10. A pre-lab handout and introductory laboratory lecture illustrate how IQ modulators are used to generate arbitrary digital modulation constellations in the I-Q plane. An example completed IQ modulator is shown to students demonstrating the basics of high frequency signal routing with short lead lengths and good grounding. Each student then individually solders together the IQ modulator assembly in a process that can be done in about 2 hours.

A wireless communication link is then demonstrated by having one student using their assembly as an IQ modulator and a student partner using their assembly as an IQ demodulator. The IQ modulator uses a function generator input and the IQ demodulator uses an oscilloscope as the receiver. Students can directly witness the importance of having the local oscillator of the transmitter phase locked to the local oscillator of the receiver in order for the digital communication link to be successful. Students also compare Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK) and higher order constellations as part of the characterization of the digital links.

Student feedback on the IQ Modulator/Demodulator project centers on how the soldering and high frequency layout of the project are eye-opening compared to early laboratory activities in the curriculum. Students also report a much more in-depth understanding of I-Q modulation techniques as they use more capable VSA/VSG and SDR equipment in future laboratory sessions.

INRODUCTION TO I – Q MODULATORS

In-phase and Quadrature modulators (I-Q modulators) are used in many modern wireless communication systems to modulate the amplitude and phase of a wireless carrier signal with digital information. They are essential blocks in understanding how wireless digital communication systems operate. Modern digital communication teaching and research laboratories can use commercial test and measurement instrumentation to simulate complex digital I-Q modulation scenarios. These full-featured instruments are great to use but it is easy to over-look the fundamental operational principles of creating these complex waveforms at the physical layer of the system. In order to give students direct insight on the operation of I-Q modulators, a laboratory exercise was created to teach the fundamentals of I-Q modulator operation with a simple laboratory kit consisting of frequency mixers, semi-rigid coaxial cable with connectors, and surface mount resistors. The schematic of the I-Q modulator is given in figure 1 as drawn in the Keysight Advanced Design System analysis program.

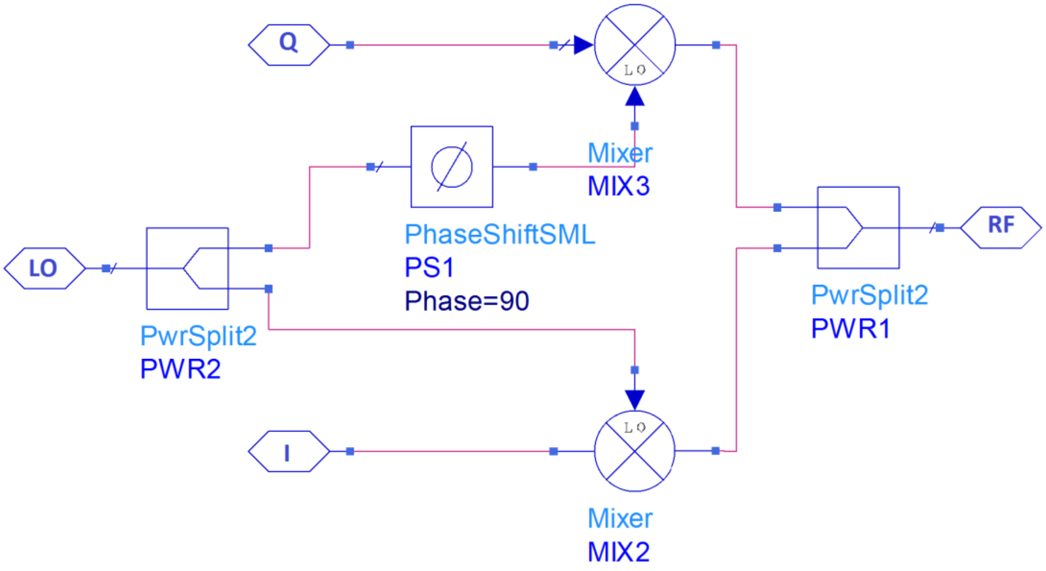

Figure 1: an I-Q modulator has an in-phase "I" and quadrature "Q" data input. The digital input signals must be symmetrical above and below ground potential with a "high" level being a positive voltage and a "low" being a negative voltage. The "LO" signal is at the carrier frequency and is split through the PowrSplit2 component into the Local Oscillator ports of the frequency mixer. The "Q" mixer MIX3 has an extra 90 degrees phase shift compared to the "I" mixer. This modulator can be used both as a modulator with the "I" and "Q" ports as inputs or as a demodulator with the "I" and "Q" ports as outputs.

The bill of materials for the I-Q modulator laboratory construction and characterization project is shown in Table 1. The frequency mixers MIX2 and MIX3 are purchased from the company “mini-circuits” and cost $3.95 each for a surface mount package component. They are designed to work up to a frequency of 1 GHz and have a DC coupled IF port. The frequency mixers require a Local Oscillator power drive of 4 dBm.

Table 1: Bill of materials for the I-Q modulator block diagram shown in Figure1.

Reference Designator	**Part Number**	**Qty**
MIX2, MIX3	Adex-10L+ (minicircuits)	2
PWR1, PWR2	3 16 ohm 0805 Surface mount resistors	2
PS1	Semi-Rigid Coax (UT-085-TP-M17) with SMA connectors	1

The power splitters and combiners, Pwrsplit 2, in figure 1 are implemented with 16.6 ohm surface mount resistors configured in a Y network to form a broadband passive splitter. This passive splitter has a 6 dB insertion loss as measured in a 50 ohm measurement impedance environment. The 90 degree phase shifter, PhaseShiftSML, is implemented with a longer coaxial cable section to the “Q” mixer compared to the “I” mixer. All interconnections between components are made with 0.085 inch semirigid coaxial cable.

LABORATORY I-Q MODULATOR CONSTRUCTION OVERVIEW

The I-Q modulator was constructed on top of a piece of copper clad pc board material. The construction technique is “dead-bug” where all components are soldered on to the pc board ground plane. A photograph of the completed I-Q modulators is shown in Figure 2. A center frequency of 100 MHz to 1 GHz is often chosen based on the frequency range of the mixer and rf source availability. 915 MHz is a common choice since this is an unlicensed band frequency. Amateur radio bands at 144-148 MHz or 420-450MHz is also a good choice if the students have FCC licenses[1]. The project starts by construction of the semirigid coaxial assemblies with SMA connectors. The connectors need to be soldered on to the coax and the author finds that this soldering activity is extremely instructive to students as they often have insufficient soldering practice. The soldering of SMA connectors on to 0.085 inch semirigid coax does require good skill in order to provide proper operation. The choice of soldering position on the PC board ground plan also offers teachable moments on the importance of keeping lead lengths short. The coax cable connection to the ground plan also teaches that one has to consider both the signal current path and ground current path when working at high frequencies. Figure 3 and figure 4 show close ups of the solder interconnections near the frequency mixers. The three 16 ohm resistors that form the power splitter are also shown. The handling of surface mount resistors with soldering irons is also a key part of the learning objectives of this laboratory.

Figure 2: This is a photograph of a completed I-Q modulator assembly. 0.085 inch semirigid coaxial cable assemblies are soldered on to a printed circuit board ground plane. The surface mount mixers are mounted upside down (dead bug construction) and interconnect to the coax and to the power splitters. The power splitters are made from three 16 ohm surface mount resistors in a Y network but are hard to see in this photograph. Figures 3 and 4 show the detail of the soldering around the mixers much better. The 4 ports of the I-Q modulator are labeled. The "LO" or Local Oscillator port controls the switching of the mixers. The "I" and "Q" ports are used as data inputs or data outputs. The "RF" or Radio Frequency port can be used as the modulator output or demodulator input.

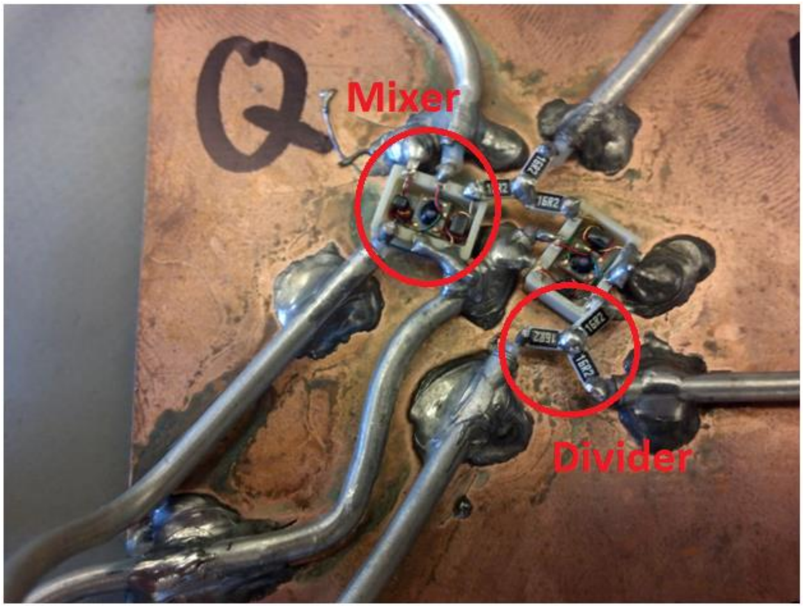

Figure 3: This photograph shows detail of the construction and soldering of the coaxial cable elements. The frequency mixers and the power splitters and power combiners are highlighted. It is very important to ground the coaxial cable to the ground plan at the points of exit to the mixer and power splitters in order to NOT attenuate the high frequency signals. The soldering of the three 16 ohm resistors in the power splitter also provides a challenging experience for students in handling of surface mount components.

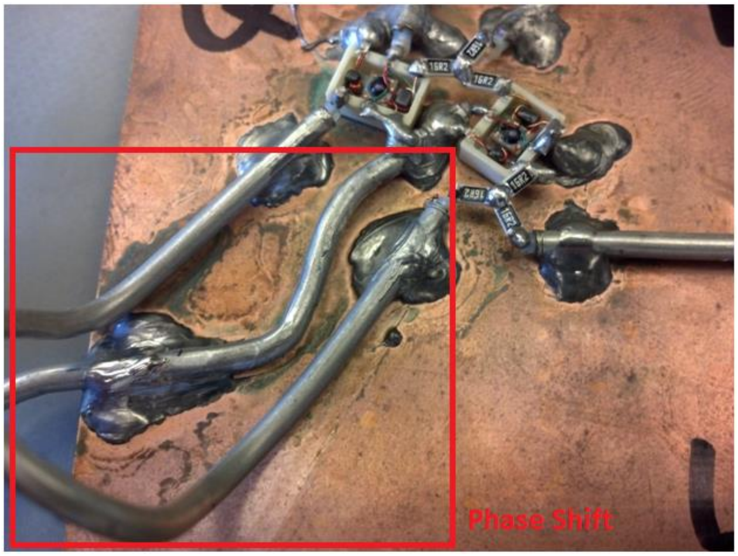

Figure 4: This photograph shows additional detail on the 90 degree phase shift section of the I-Q modulator. The local oscillator input comes in on the right hand side of the photograph. The Y-network power splitter then puts one output signal directly on the "I" mixer. The red box in the photograph highlights the additional coaxial cable section length that is used before the local oscillator is applied to the "Q" mixer.

VALIDATION OF THE DESIGN

After the I-Q modulator is constructed, the modulator is characterized for its performance. Figure 5 shows a picture of the test equipment that is used. Figure 6 shows a block diagram of the test system arrangement.

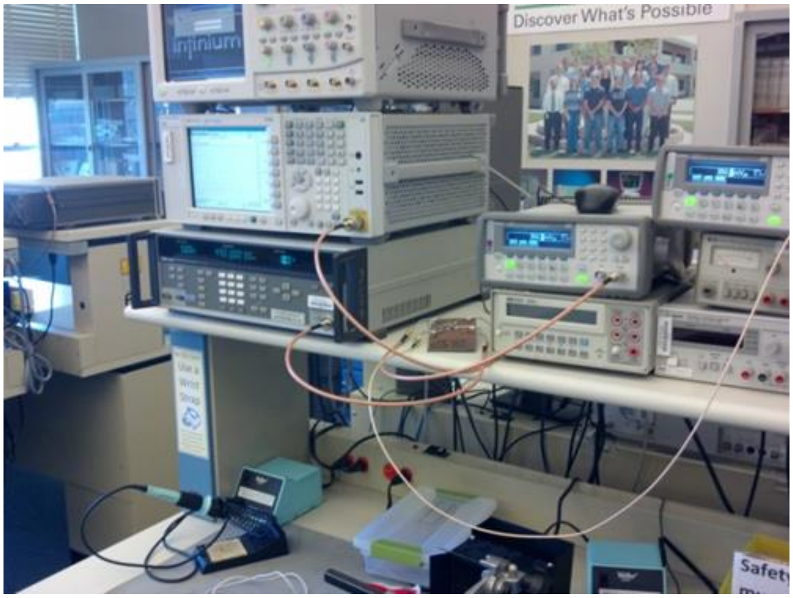

Figure 6: This photograph shows the test system that is used to characterize the IQ modulator that the laboratory exercise has students build. The required equipment is a radio frequency source, electronic spectrum analyzer, a two output function generator and a high frequency oscilloscope.

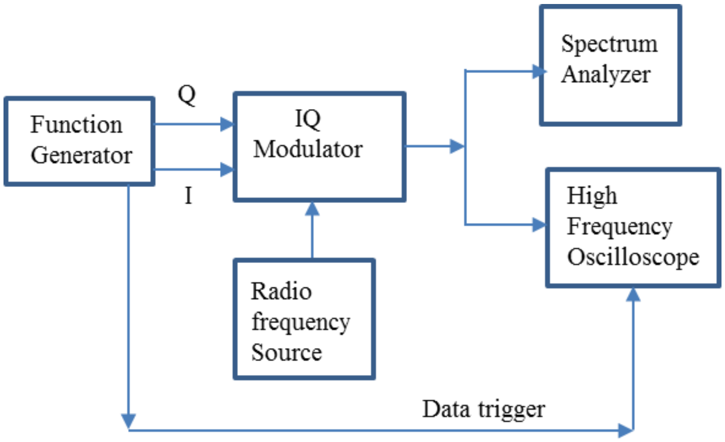

Figure 7: The Function generator has two digital outputs that swing symmetrically above and below ground potential. Common practice is to use a square wave output with the “Q” frequency being twice the “I” frequency. This produces a Quadrature phase shift keying (QPSK) output from the modulator. Higher level modulation such as 16 QAM is also easily realized with multiple level modulation into the “I” and “Q” ports.

TEST PROCEDURE:

To test basic functionality of the I-Q modulator, the performance of both the “I” and “Q” sections of the modulator is done separately and sequentially. First only an “I” signal is applied to the modulator and the output is observed using an electrical spectrum analyzer. With only a single input the IQ modulator, the output will perform as a Binary Phase Shift Signal (BPSK) modulator. Figure 8 shows an example output as found in the electrical spectrum analyzer. After the I-modulator is verified, the function generator is only applied to the “Q” input and that modulator performance is verified. Both inputs are then applied to the modulator. The outputs are then examined in both the frequency domain (with the spectrum analyzer) and the time domain (with the oscilloscope).

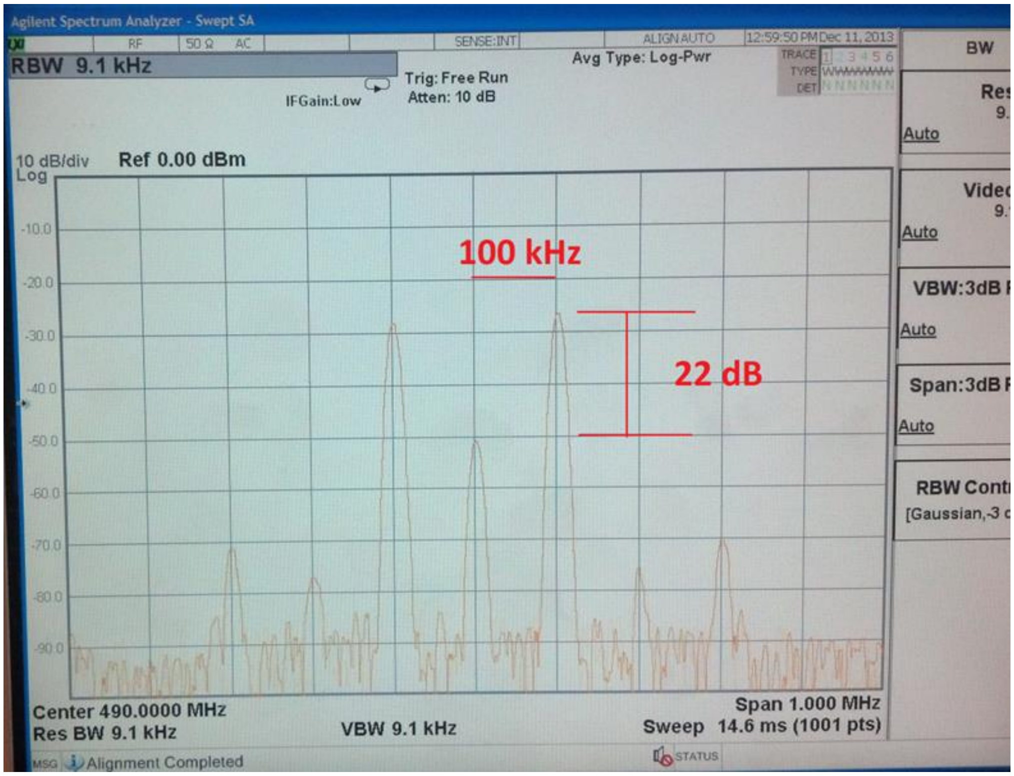

Figure 8: This image shows the output of the I-Q modulator with a 100 KHz sinousoidal signal applied to the “I” input and a 490MHz signal applied to the Local Oscillator port of the I-Q modulator. One can see the upper and lower sidebands spaced at 100kHz from a suppressed carrier at 490 MHz. The suppression of the 490 MHz carrier depends on the ADEX 10-L+ mixer specification but especially on the quality of construction of the student built modulator. This modulator shows 22 dB carrier suppression.

I-Q MODULATOR LINK PORTION OF THE LABORATORY EXERCISE

When multiple laboratory groups finish characterization of the individual modulators, the groups will pair-up to demonstrate a full digital communication link. The block diagram of the experiment is shown in figure 9:

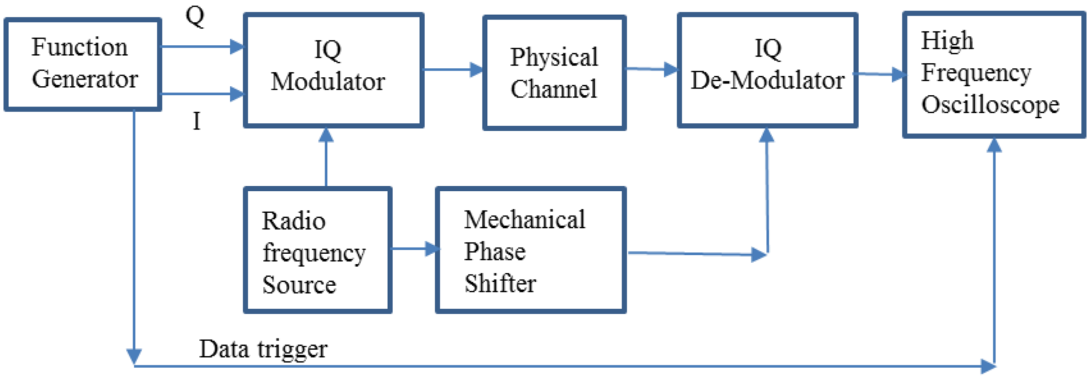

Figure 9: A full digital communication link can be created by cascading an I-Q modulator, a channel, and I-Q demodulator in sequence. For this design, the I-Q modulator and the I-Q modulator are identical designs. The Physical Channel can be a length of coaxial cable. The Physical Channel could also be constructed as a delay-line interferometer with two lengths of coaxial cable to simulate multi-path signal environments. The mechanical phase shifter here is used to adjust the phase of the receiving demodulator with respect to the incoming signal. The students can directly witness the importance of having proper phase alignment by watching the demodulated outputs in the high frequency oscilloscope as a function of the phase shift in the mechanical phase shifter.

STUDENT FEEDBACK AND OUTCOMES OF THE STUDENT BUILT I-Q MODULATOR PROJECT

This I-Q modulator laboratory learning experience has now been run as a laboratory exercise in a digital communication laboratory course for 4 years. The modulator construction and evaluation is the first experiment set for the laboratory course. The I-Q modulator construction and evaluation experiment set takes about three weeks to accomplish meeting three hours per week. The I-Q modulator construction exercise is followed by full characterization of digital communication links with commercial Vector Signal Generators and Vector Signal Analyzers. This laboratory instructor finds that students have a much more detailed understanding of the digital communication modulation process in the later portions of the 10 week laboratory as a result of these very hardware oriented, physical layer results from the IQ modulator project. Students get a great introduction to high frequency design, use of semirigid coaxial cable, and deadbug construction techniques. The primer in high frequency test equipment use also helps the laboratory exercises to be more successful for later experiments in the course.