Application Note

Frequency Up-Conversion for Arbitrary Waveform Generators

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Instruments

Applications: Quantum Computing, Quantum Sensing, NMR, MRI
Products: UHFLI, UHF-AWG, HDAWG

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Motivation

Many of today's approaches to build a quantum computer require the reliable generation of arbitrary microwave signals in the 4.5 to 9 GHz regime for qubit manipulation and readout. While signal timing, resolution and low noise are of utmost importance, the signal modulation bandwidth required is usually limited to a couple of hundreds of MHz. Even though there are arbitrary waveform generators available for the GHz regime, they come with substantial downsides regarding cost, vertical signal resolution and usability, e.g. time to program, when compared to the up-conversion approach described here. This technical note gives a detailed description and list of components required for up-converting the In-phase (I) and Quadrature (Q) signals provided by a Zurich Instruments HDAWG, a multi-channel Arbitrary Waveform Generator with up to 750 MHz bandwidth and eight analog output channels, to 8 GHz. The design and assembly of an up-conversion board and key parameters which specify the quality of conversion are discussed in detail. This is useful not only for circuit quantum electrodynamics (QED), for which it had been designed and thoroughly tested, but also for applications like magnetic resonance and others [1, 2].

Single-Sideband Mixing

We use single-sideband mixing in order to shift a signal in frequency space from DC to the band between 4.5 and 9 GHz while maintaining signal quality. The central component for frequency up-conversion is an analog mixer, that multiplies the input signal from the AWG with a local oscillator signal. Most mixers use the non-linearity of a diode or a transistor to generate the product of two voltages, which is then used as an output optionally after additional conditioning. If the applied signals are sinusoidal it can easily be shown with a trigonometric identity, that the result will consist of the sum and difference of both input frequencies as visualized in Figure 4,

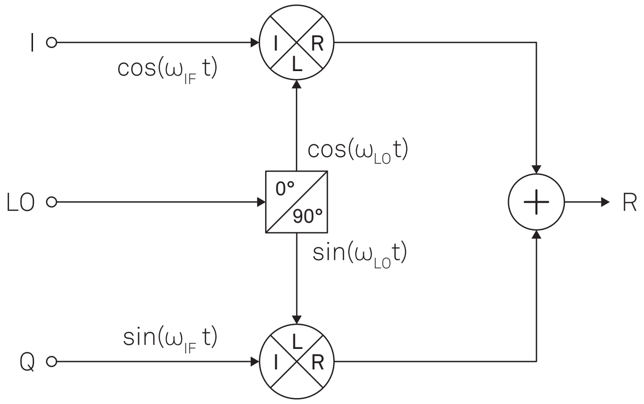

Figure 1. Schematic illustration of an IQ-mixer composed of two separate mixers, a 90°-hybrid coupler to phase-shift the LO signal and a combiner to join both mixing results.

$$\cos(\omega_{\mathrm{LO}} t) \cdot \cos(\omega_{\mathrm{IF}} t) = \frac{1}{2}\left[\cos\left((\omega_{\mathrm{LO}} - \omega_{\mathrm{IF}})\, t\right) + \cos\left((\omega_{\mathrm{LO}} + \omega_{\mathrm{IF}})\, t\right)\right]. \tag{1}$$

For our application it is important to completely eliminate one of the sidebands, as it reduces the power in the desired component and adds unwanted interference and heating into the setup. This can be achieved by adding a second mixer that operates at the quadrature component of the local oscillator and adding the

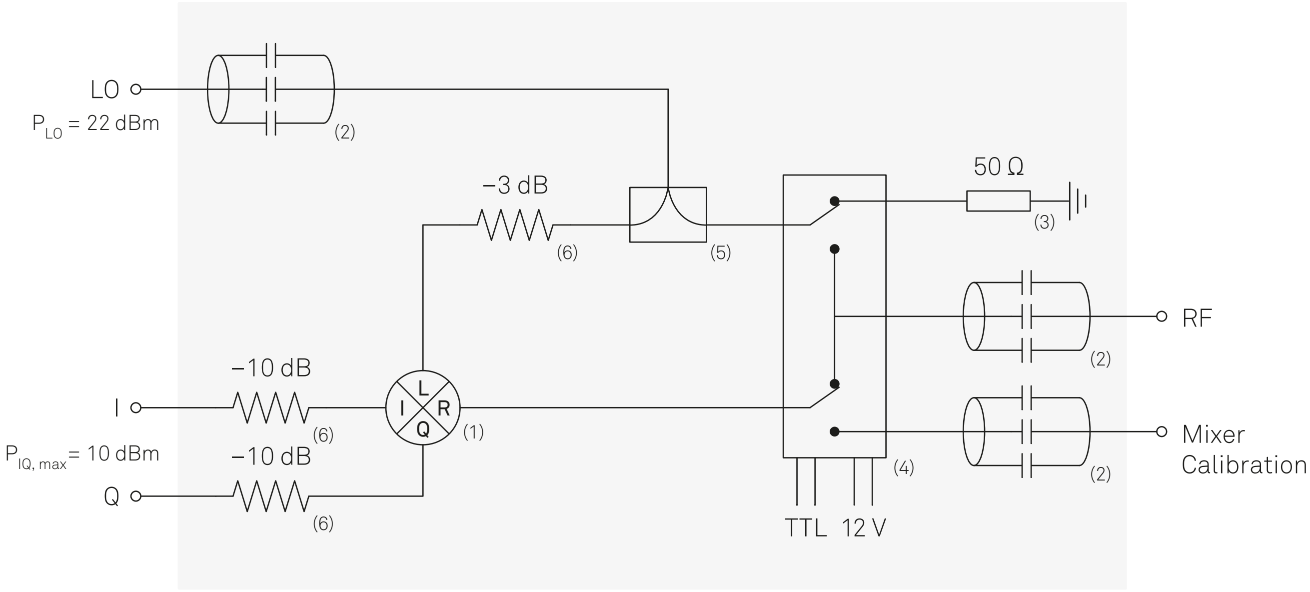

Figure 2. Schematic of a typical up-conversion board as it was developed at ETH Zurich [3]. It is composed of: (1) IQ-Mixer, (2) DC-Block, (3) Terminator, (4) SP3T-Switch, (5) Microwave Splitter and (6) Attenuators.

two mixer outputs coherently with a combiner. This complex modulation scheme is called IQ-mixing and often employed in communications engineering. The block diagram of an IQ-mixer is shown in Figure 1. By calculating the resulting spectra using Equation 1, we observe that one of the sidebands will vanish if the relative phase offset of I and Q is ±90°. Due to the exponential characteristics of the mixing diode, higher order mixing terms will always be present in the output spectrum and cause unwanted side effects like LO leakage, higher order harmonics and image suppression.

Implementation

To assemble such a frequency conversion stage, Figure 2 shows a typical setup as it was developed by the Quantum Device Lab (QuDev) at the ETH Zurich for circuit QED experiments [4]. It features an additional calibration output and the possibility to directly feed the LO signal through for switching to a continuous wave mode. Table 1 provides detailed information about the components used, their manufacturers and their approximate price. All components have SMA connectors and can easily be connected via semi-rigid SMA cables, as shown in Figure 3. If a different operating frequency range is required, this setup can easily be adapted by replacing the mixer with a different model (e.g. IQ-0307 or IQ-0618 from Marki Microwave). The key parameters when selecting a suitable mixer for this application are high image rejection (~25 dB), high LO to RF isolation (~25 dB) and low conversion loss values (~6.5 dB). The numbers in brackets give the specification parameters from Marki Microwave as a reference. Please note that these parameters also depend on the chosen frequency range.

Apart from the IQ-mixer, the circuit contains a power splitter (5) and a 2P3T switch (4) to be able to select between experiment, calibration and a direct LO feedthrough. The output signals of the AWG are attenuated by 10 dB to reduce broadband noise and reflections at the inputs of the IQ mixer. To protect our setup from any unwanted ground loops, we introduce broadband DC blocks to the respective inputs and outputs to establish a galvanic isolation. In order to characterize our setup we use two ports of our HDAWG to provide sine waves with adjustable phases, amplitudes and DC offsets to the dedicated IQ-inputs on our board. The SMA cables used for this purpose should have low loss values and the lengths should also be matched to avoid any extra group delay and amplitude imbalance. An RF signal generator (SGS100A from Rhode&Schwarz) is used to drive the LO input and for calibration purpose a spectrum analyzer captures the resulting output from the board. In addition, the com-

Label	Part ID	Manufacturer	Price
(1)	IQ-4509MXP	Marki Microwave	1200 $
(2)	INMET 8093	API/Inmet	80 $
(3)	ANNE-50X+	Mini-Circuits	15 $
(4)	SHX801-02	SHX	90 $
(5)	ZX10-2-1252+	Mini-Circuits	70 $
(6)	BW-S3(10)W2+	Mini-Circuits	30 $

Table 1. List of components with their approximate price.

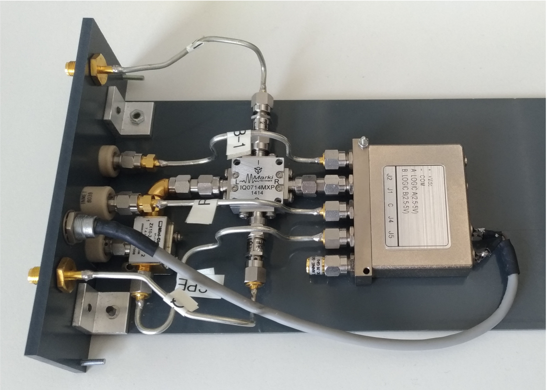

Figure 3. Photo of the up-conversion board.

plexity of the up-conversion board can be significantly reduced by removing the non-mandatory components (3), (4) and (5), if a continuous wave mode and a separate calibration output are not required.

Setup and calibration

To achieve the best possible spectral properties, setup and calibration is usually done in the following order:

Optimization of signal power

Usually we start by adjusting the power levels impinging on the mixer to be at the sweet spot of the specification. This is important to suppress additional unwanted spectral components at multiple integer values of the AWG frequency f_{IF}. The power values for the LO drive and the IQ-ports are stated in the datasheet of the mixer. In our case the datasheet requires a LO drive level of +13 to +16 dBm and specifies an input 1dB-compression point of +9 dBm for both IQ-channels. In order to calculate the necessary signal power at the inputs of the board, we have to take into account the total attenuation of components between the terminals of the board and the mixer. To keep the presence of the higher harmonics as low as possible, one should consider using IQ-power levels which are several dBm lower than the aforementioned compression point (in our case P_{IQ}=5 dBm). A subsequent RF amplifier could then be used to reach the required application specific power levels. Furthermore, low-pass filtering the output signal could be interesting for applications where the higher order harmonics of the LO-frequency are of concern. For calibration purposes, the AWG frequency should be set to a continuous mode and calibration should be repeated whenever the LO frequency is changed.

Var.	Value	Description
f_{LO}	8000 MHz	LO Frequency
f_{IF}	10 MHz	AWG Frequency
P_{LO}	22 dBm	LO Power
P_{IQ}	5 dBm	AWG Power
$V_{\mathrm{DC,I}}$	-48.5 mV	DC offset I
$V_{\mathrm{DC,Q}}$	+6.0 mV	DC offset Q
$\Delta\varphi_{\mathrm{IQ}}$	82.80°	Phase offset
ΔA_{IQ}	-1.35 %	Amplitude Imbalance

Table 2. Example setup and calibration values. Note that these values are only for reference and are strongly dependent on the specific setup.

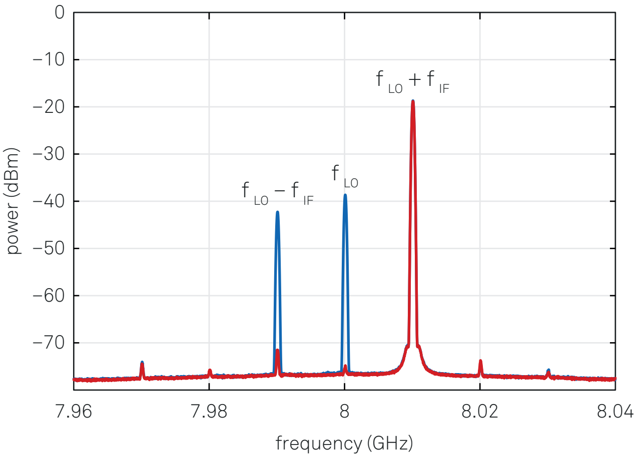

Figure 4. Spectra of the up-converted signal. The blue (red) line was recorded before (after) calibration.

LO Leakage

Due to a finite resistance of the mixing diode, some DC voltage will drop across its junction, which will lead to a leakage of the LO frequency to the output. This DC voltage can be eliminated by a contrary DC offset on the respective I- and Q-channel. This can be achieved by sweeping both DC offsets of the I- and Q-channel with the LabOne® Software until the LO leakage is suppressed by approximately 30 dB. Please note, these parameters depend on the temperature of the device. Calibration should therefore be conducted when the mixer has reached its steady-state temperature and redone in case the operating conditions such as the ambient air temperature change.

Image Suppression

Image suppression is specified by the amount of power distributed among unwanted image frequencies. It depends on two parameter settings. First, the deviation of the relative phase offset between I and Q from ±90°. Imperfections in the cable lengths and internal mixer components need to be compensated. Second, any amplitude imbalance between the I- and Q-signals has also to be compensated. We calibrate the suppression of our image by sweeping the relative phase starting from 90°. When a local minimum is found, we adjust the ratio of both I- and Q-amplitudes and repeat the routine until the optimum is reached. Table 2 provides typical values, which were obtained by manual calibration.

Automation

Based on measurement data from a spectrum analyzer, calibration can also be automated by solving two independent optimization problems. The first optimization covers the adjustment of the I- and Q-offset to suppress the LO-leakage and the second problem deals with phase and amplitude imbalance to lower the unwanted sideband. To implement such automated routines, the Nelder-Mead optimization method turns out to be very useful since it converges relatively quickly to the desired optimum for both problems [5]. Typical image suppression values, which can be reached by an automated calibration routine, are roughly 40 dB.

Characterization

Ideally, the output spectrum should only show one frequency component and the two other peaks at f_{LO} and f_{LO}-f_{IF} should be completely suppressed. The parameters listed in Table 2 lead to the spectrum shown in Figure 4. The manually calibrated red line exhibits an almost perfect elimination of the LO leakage at 8 GHz and an image suppression of roughly 50 dB. The higher order harmonics at multiple integer values of 10 MHz are still visible, but only a few dBm over the instrument noise floor. This verifies that the combination of our HDAWG and the presented up-conversion board is able to expand its scope of operation to a frequency range above several GHz.

Acknowledgements

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