

▶ **Application Note Spectrum DDS in Quantum Research**

A new versatile tool in the Quantum research toolbox

The arbitrary waveform generator (AWG) is among the most powerful and flexible signal sources available for quantum research. AWGs can generate an almost infinite number of waveforms within the generator's bandwidth and the length of its waveform memory. Once you have the AWG you will need to fill it with useful waveforms. Traditionally, waveforms are recorded with a digitizer or generated with application software and sent to the AWG, the new DDS-option changes this paradigm!

In 2024 Spectrum Instrumentation has introduced a new direct digital synthesizer (DDS) option for its range of 16-bit AWGs. DDS is a method for generating periodic waveforms from a single, fixed-frequency reference clock. Spectrum Instrumentation's DDS option for AWGs uses multiple 'DDS cores' to generate a multi-carrier (multi-tone) signal with each carrier having a well-defined frequency, amplitude, and phase.

The DDS option greatly reduces the complexity and number of data points required for generating one, or several sine-waves, on a single output channel. The DDS option was developed in direct cooperation with a number of quantum researchers, especially with the team of the Rymax One Consortium (<https://rymax.one/>) to the needs of modern quantum research. In this Application Note, we will highlight using the new option for Quantum research projects.

Driving Acoustic Optic Deflectors / Modulators (AOD/AOM)

Acousto-Optic Modulators (AOMs) or Deflectors (AODs) are widely used to have dynamic control over the frequency (wavelength), amplitude and angle (position) of laser light. They typically consist of a crystal that is in contact with a piezo-transducer (actuator) and absorber. The piezo-transducer is driven by an amplified Radio-Frequency-signal (RF) typically in the range of 10 MHz to 1 GHz. The actuator induces a pressure wave in the crystal that periodically changes the local refraction index of the crystal [1].

Diffraction

Light coming from a light-source, typically a laser, diffracts on the crystal lattice due to Bragg diffraction. This leads to a multitude of diffraction orders and hence light beams. Each of these beams is diffracted by an angle θ_B that satisfies the Bragg condition:

$$\sin \theta_B = m \frac{\lambda}{2\Lambda}$$

Where $m = \dots, -2, -1, 0, +1, +2, \dots$ is the diffraction order, λ is the wavelength of the light in vacuum and Λ is the wavelength of the sound wave. Note that the $m = 0$ order is not diffracted and continues in the same direction.

Frequency

Since the sound wave in the crystal is moving from the actuator to the absorber, the light that is diffracted from the wave experiences a Doppler shift (or if you prefer absorbs one or more phonons) and its final frequency (f_m) is given by:

$$f_m = f_0 + mF,$$

where f_0 is the frequency of the incoming light (typically several 100s of THz) and F the frequency of the sound wave which correspond to the frequency of the coupled RF-signal.

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Intensity

The efficiency of the diffraction is characterized by the fraction of light in the 1st diffraction order (I_1) with respect to the amount of incident light (I_0) and is given by:

$$\frac{I_1}{I_0} = \sin^2 \left(\frac{\pi}{2} \sqrt{\frac{P}{P_0}} \right),$$

here P is the RF-signal power and P_0 an efficiency parameter that depends on how well the power from the RF-signal is coupled to the crystal and finally the light.

Full-control over the laser light

If we consider for example the 1st-order diffraction beam, from the above it's clear that the RF-signal controls the angle of the laser beam (after a lens this corresponds to a position), as well as the frequency and intensity of the light. These features make control over the RF-source a vital part of controlling laser light. This is where Spectrum Instrumentation's AWGs (e.g. M4i.66xx-x8 series) come into play. Especially, in combination with the new DDS-option, these devices are the ideal tool for generating the required RF-signals to control the AOM/AOD.

Optical setup for AODs

In Figure 1, we show a possible setup for using the Spectrum Instrumentation AWG with an AOD. The RF-signal (of the order of 100 MHz) coming from the AWG is sent through a 5W amplifier from Mini Circuits (ZHL-5W-1), to an RF-coupler (ZDC-20-1+), which sends part of the signal (about 20 dB suppressed) to a spectrum analyzer (Siglent SSA 3075X-R) and the main output to the AOD. A cleaned-up low-power laser beam, coming from an optical fiber, is passed through a polarizing beamsplitter cube (PBS) and sent through the AOD. The diffracted +1 order beam coming from the AOD is sent either to a camera, or a white-screen for imaging.

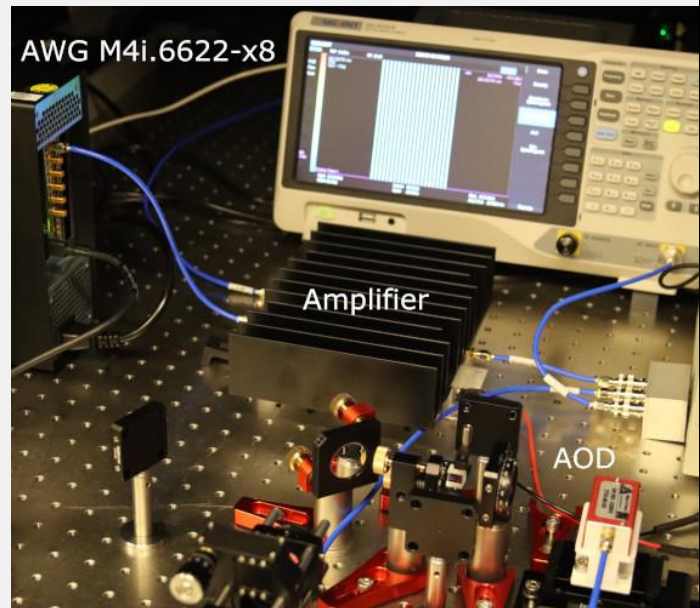


Figure 1: Optical bench setup for controlling an AOD. In the left top corner there is an AWG M4i.6622-x8 inside a PCIe docking station. In the middle there is an RF-amplifier (MiniCircuits ZHL-5W-1). In the right bottom corner, there is an AOD (AA Opto Electronic DTSX-400).

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Programming the AWG – DDS-option

On [Spectrum Instrumentation’s website](#) or the [GitHub repository](#) (Python-only), there is a multitude of examples available for different programming languages. In the following we’ll limit ourselves to the new Python package. To use the Python package, start by reading the Tutorial on GitHub, which explains the Installation and Basic usage. Here, we’ll use the DDS-firmware option, for DDS-dedicated examples please see the [dds-examples folder](#) on GitHub.

We’ll assume that a Card object is initialized and stored in the variable card and the required channels are enabled and a Channels object initialized in the variable channels. Then the code for generating a single carrier is:

```
# Setup DDS functionality
dds = spcm.DDS(card, channels=channels)
dds.reset()

# Start the test
dds[0].amp(50 * units.percent)
dds[0].freq(10 * units.MHz)

dds.exec_at_trg()
dds.write_to_card()
```

Code 1. A single carrier with 50 % of full range amplitude and a 10 MHz frequency.

When the card trigger arrives, this code snippet generates a sine wave with 10 MHz frequency and an amplitude that is 50% of the full amplitude range. The resulting signal is shown on a spectrum analyzer (the output range was set to ±1000 mV) in Figure 2.

Multi-carrier signals

Especially useful for AODs is the multi-carrier functionality of the DDS-firmware. The current firmware enables the user to define up to 20 carriers on a single channel. Each of these sine waves creates a running density wave with a certain wavelength in the crystal. The running waves each act as diffraction gratings on the light, hence creating multiple diffraction patterns. If we focus on the 1st-order diffraction pattern, the AOD will create 20 beams with different angles and intensities, each of them being defined by the equations above. Therefore, when we control the frequencies and amplitudes of the individual carrier signals, we’re able to have full control over the position (angle) and intensity of each of these laser

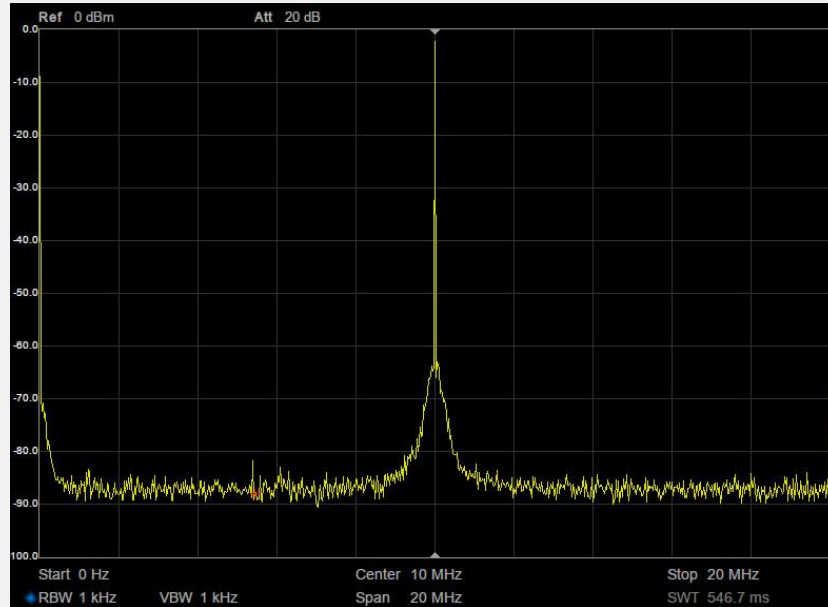


Figure 2: The spectrum on a single 10 MHz, -2 dBm carrier signal generated with the DDS-firmware on an AWG.

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beams.

In Figure 3, a schematic depiction of this system is shown. The Spectrum Instrumentation AWG (M4i.66xx-series) creates a signal with 20 tones, with full control over both frequency and amplitude, which is amplified by an RF-amplifier (for example MiniCircuits ZHL-5W-1) and then sent to the AOD (for example AA Opto Electronic DTSX-400 series). The laser that is transmitted through the AOD is diffracted and, in the 1st-order, there are now N beams with full control over angle and intensity.

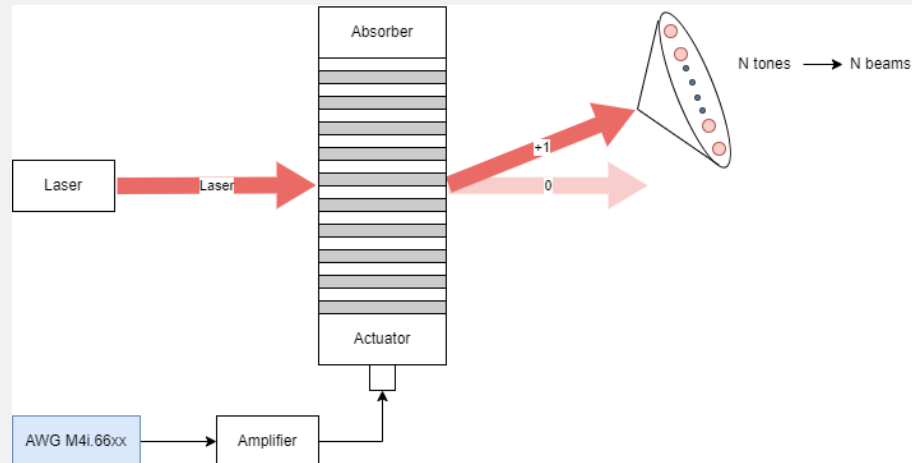


Figure 3: Typical setup for an AWG that drives an AOM / AOD with N frequencies. A laser beam is diffracted by the AOM and N beams are generated.

Programming 20 carriers is, using the Python package `spcm`, straight-forward. In the code-snippet below, we show how these tones are programmed. As before, we initialize a DDS object with a card object and the channels object. Then the DDS firmware is reset. Using NumPy and the Pint units package, we create an array with values from 90 to 109 MHz in steps of 1 MHz. Then we cycle through all the DDS-cores (20 in case of 1 active output channel) and set the amplitude and frequency of each channel.

```

dds = spcm.DDS(card, channels=channels)
dds.reset()

init_freq = np.array([ 90, 91, 92, 93, 94, 95, 96, 97,\
                      98, 99, 100, 101, 102, 103, 104, 105,\
                      106, 107, 108, 109]) * units.MHz

for core in dds:
    core.amp(45 * units.percent / len(init_freq))
    core.freq(init_freq[core])
dds.exec_at_trg()
dds.write_to_card()

```

Code 2. 20 carriers with frequencies from 90 to 109 MHz in steps of 1 MHz.

The resulting electrical signal is shown in Figure 4. The energy spectrum of a multi-carrier signal with 20 tones from 90 to 109 MHz in steps of 1 MHz. Figure 4 shows a plot coming from our spectrum analyzer. On the horizontal axis, there is the frequency axis from 87.5 MHz up to 112.5 MHz and a recording is done with a resolution bandwidth (RBW) of 1 kHz. On the vertical axis, we see the power spectrum of the signal into a 50 Ohm load. As we see, there are 20 carriers.

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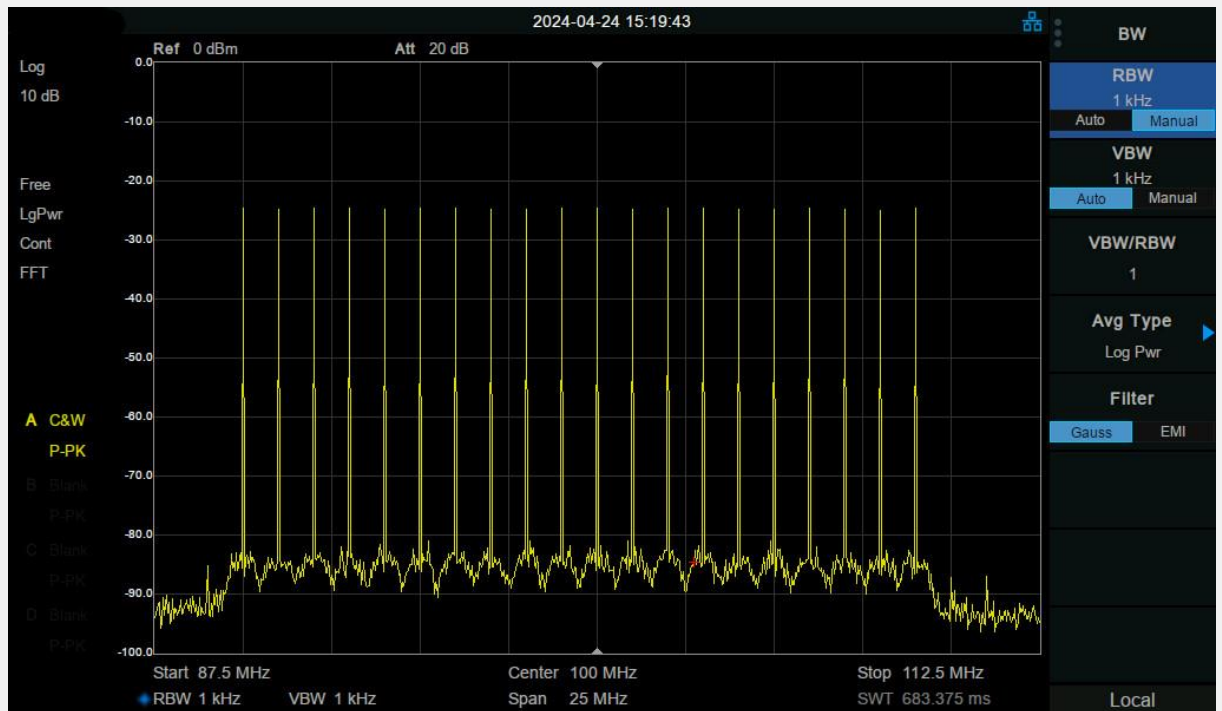


Figure 4. The energy spectrum of a multi-carrier signal with 20 tones from 90 to 109 MHz in steps of 1 MHz.

When sending this signal (please always start with a very low power so that you don't break the crystal) to the AOD, the laser beam transiting the crystal is diffracted and the resulting 1st-order diffraction pattern, after a lens, is shown in Figure 5. Each of these beams can be moved (change of carrier frequency) and/or made lighter or brighter (change of carrier amplitude). If for example atoms are trapped in the center of these beams, changing the frequency of a single carrier moves the atom around.



Figure 5. Camera image of a screen with the 1st-order diffraction pattern of a laser. The laser is passing through an AOD that is supplied with a multi-tone signal with 20 carriers.

An example of changing the frequencies of the carriers of the RF-signal is shown in Figure 6. The image shows a power density plot over time (real-time spectrum analysis). The top part of the plot corresponds to the signal at time = 0 s and the bottom to the signal after 15 seconds. We start with 20 carriers and after about 3 seconds, 9 carriers are turned off and the resulting carriers are moved together on the original frequency grid. This procedure is very useful for neutral atom quantum computers, because each of the carriers would correspond to a tweezer. Imagining that after the atom loading, the tweezers 2, 5, 6, 8, 12, 13, 15, 17, 20 are empty. We can turn these carriers off (the line stops) and the tweezers that contain atoms (1, 3, 4, 7, 9, 10, 11, 14, 16, 18, 19) are moved together using s-shaped ramps

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to minimize heating due to the moving of the atoms.

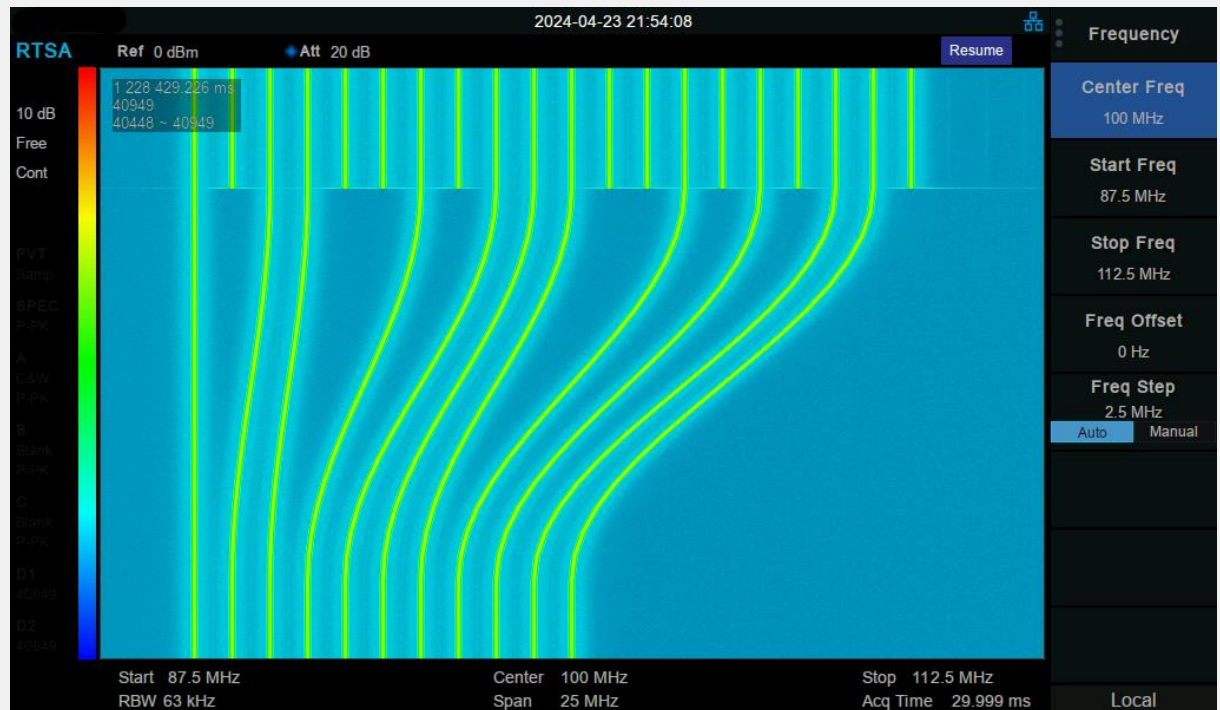


Figure 6. Power density spectrum of a multi-carrier signal on a real-time spectrum analyzer (RTSA). The horizontal axis corresponds to frequencies from 87.5 to 112.5 MHz and the vertical axis to time from 0 (top) to 15 seconds (bottom). The color scale corresponds to the power density at a frequency, where blue corresponds to low power and yellow to high power. The yellow lines hence, correspond to the carriers.

The full code-snippet showing the code required for the image above is available as separate document.

Summary

The new DDS-firmware option is tailored to typical uses in the field of quantum research, without being limited to this field (see the [Non-Quantum AN]). In this application note, we've investigated one specific use of the DDS-firmware: controlling AOMs/AODs. The DDS-option enables users to directly control the number of laser beams (number of carriers), their position (carrier frequency) and intensity (carrier amplitude) using the direct connection between RF-signal carriers and diffracted laser beams. Furthermore, the DDS-option has built-in linear dynamic behavior, allowing the user to program a very precise change of the frequency and amplitude.

All-in-all, the new DDS-option is the ideal tool for the toolbox of the modern day Quantum Researcher!



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References

[1] AA Opto-Electronic, 2013. [Online]. Available: <http://www.aoptoelectronic.com/wp-content/uploads/documents/AAOPTO-Theory2013-4.pdf>.

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- Benno Rem, PhD – Quantum Physicist at Spectrum Instrumentation GmbH