Generation of Vector Signals at Microwave Frequencies
Application Note

Products:

- R&S®SMF100A
- R&S®AFQ100A
- R&S®SMBV100A

Vector signals at microwave frequencies can easily be generated by the direct upconversion of I/Q baseband signals. A versatile and cost-efficient solution consists of an R&S®SMF100A microwave signal generator combined with a baseband source (e.g. the R&S®AFQ100A) and an external I/Q mixer. This application note describes how to perform the frequency upconversion.

ROHDE&SCHWARZ

Application Note

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1 Note

The following abbreviations are used in this application note for Rohde & Schwarz test equipment:

- The R&S®SMF100A microwave signal generator is referred to as SMF
- The R&S®AFQ100A baseband signal generator is referred to as AFQ
- The R&S®SMBV100A vector signal generator is referred to as SMBV

Other product and company names mentioned here are trademarks or trade names of their respective companies.

2 Overview

Vector modulation is becoming more and more widespread in microwave and satellite applications. The direct generation of digital modulation at microwave frequencies is however difficult to realize and expensive. A convenient alternative for generating I/Q-modulated signals in the microwave range is the direct upconversion of I/Q baseband signals. This application note describes how to perform this frequency upconversion using the R&S®SMF100A microwave signal generator and an external I/Q mixer.

3 I/Q Mixer – Principle

Detailed information about the fundamentals of mixer operation can be found in a separate Rohde & Schwarz application note [1]. This section here describes in brief the special case of I/Q mixers. Fig. 1 shows a block diagram of an I/Q mixer for use as an up-converter (I/Q modulator).

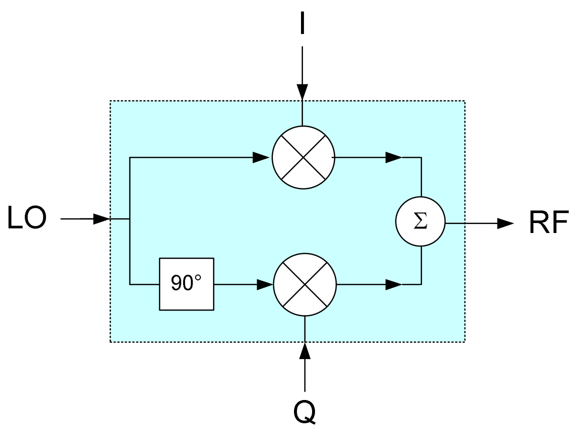


Fig. 1: Input and output signals of an I/Q mixer used as an upconverter.

The I/Q modulator requires three inputs – LO, I and Q – and it has one RF output. The I and Q signals are modulated onto the LO carrier and then added together to obtain the modulated RF signal.

I/Q mixers provide good suppression of the LO carrier and the unwanted sideband that is generated by the mixing process. Like for conventional mixers, the RF frequency results from the LO plus the IF (i.e. I/Q) frequency. When a baseband frequency offset is applied, the RF spectrum shows the wanted signal offset from the LO leakage peak and a greatly suppressed sideband signal at the image frequency. In the usual case of a zero baseband frequency offset, the RF spectrum shows only a single peak at the LO/RF frequency because the wanted signal, the suppressed LO and the sideband signal all overlay.

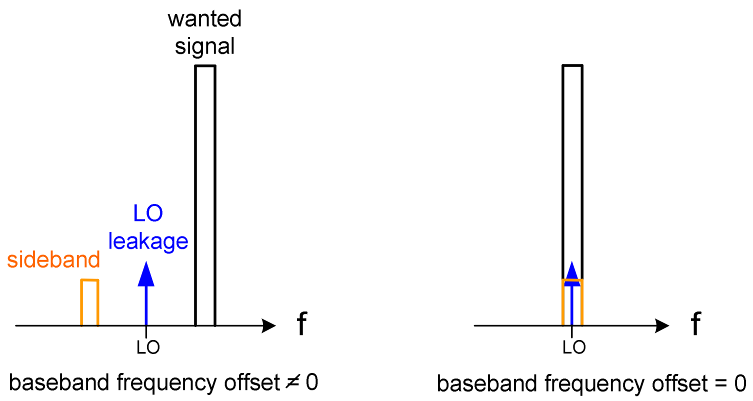


Fig. 2: RF spectrum of an I/Q mixer with and without baseband frequency offset (i.e. IF frequency).

4 I/Q versus Conventional Mixer

4.1 I/Q Mixer

The major advantage of I/Q mixers is that they provide rejection of the unwanted sideband, means they are single sideband mixers (SSB mixers). Hence, no subsequent filtering of the RF signal is required because the LO carrier and the sideband are greatly suppressed inherently by typically 30-40 dB depending on the RF frequency range. This is a very convenient feature as filtering may not be a straightforward task for certain applications (particularly when the RF frequency varies over a wide range). Additionally, I/Q mixers work directly with baseband signals. Thus, there is no need for a vector signal generator, a baseband generator is sufficient for supplying the I/Q input signals.

4.2 Conventional Mixer

While for normal operation of I/Q mixers the wanted signal overlays with the LO carrier and the sideband, the wanted sideband is spectrally separated from these signal components when utilizing conventional mixers. The later case results in a better EVM characteristic, as the unwanted signals do not interfere with the wanted signal.

5 Test Setup & Measurement

5.1 Test Setup

A vector-modulated microwave signal can easily be generated using an I/Q mixer and Rohde & Schwarz signal generators. The R&S®SMF100A microwave generator is a perfect LO source that provides radio frequency signals up to 43.5 GHz with excellent spectral purity and high output power. The I/Q signals are provided by either a baseband signal generator (e.g. the R&S®AFQ100A) or a vector signal generator (e.g. the R&S®SMBV100A). The resulting RF output of the I/Q mixer is a vector signal in the microwave frequency range. Fig. 3 shows a possible test configuration. The quality of the RF signal depends on the mixer specifications and the spectral purity of the LO signal [1]. To avoid degradation of the signal quality suitable cable must be used in this setup. The cables used for the LO and RF connections must be appropriate microwave cables.

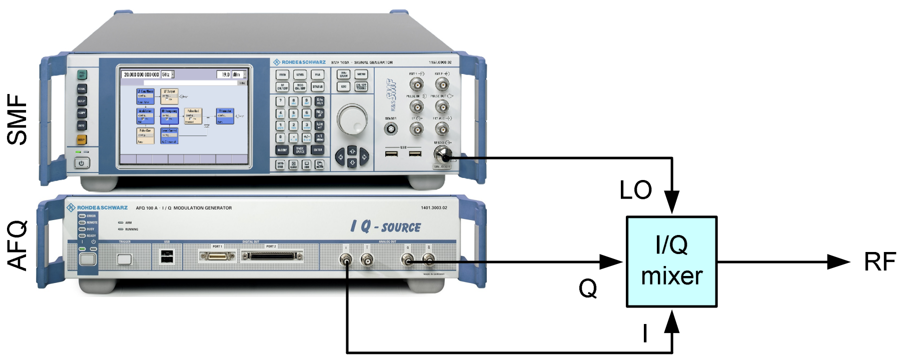


Fig. 3: Example of a test setup for vector signal generation up to 43.5 GHz using two Rohde & Schwarz signal generators and an I/Q mixer.

The SMF can provide a maximum drive power ranging between +25 dBm (at 10 GHz) and +14 dBm (at 40 GHz), which is suitable for driving the LO of the I/Q mixer. Note that I/Q mixers require high LO input power, typically around 15 dBm. The AFQ can produce I/Q signals with an adjustable I/Q level up to 750 mV (10.5 dBm at 50 Ω). Alternatives to the AFQ could be an R&S®AFQ100B, an R&S®AMU200A or an R&S®SMBV100A, for example. In this test setup we use an external I/Q mixer with the following specifications (typical values from [2]):

Mixer specifications		
Input parameters	LO power	15 - 19 dBm
	LO frequency range	22 - 32 GHz
	IF or I/Q frequency range	DC - 4.5 GHz
Output parameters	RF frequency range	22 - 32 GHz
Performance data	Conversion loss	10 dB
	Carrier rejection	40 dB
	Sideband rejection	30 dB
	1dB compression point	16 dBm
	LO-to-RF isolation	40 dB
	LO-to-IF isolation	30 dB
	Input intercept point	20 dBm
Other	Package style	Chip surface-mounted on evaluation board
	Connector type	SMA and K
	Usage	Upconverter Downconverter
	Manufacturer	Hittite

Note that I/Q mixers are offered with different package styles. They are available as a shielded module or as a chip surface-mounted on an evaluation board. The connector type must be suitable for this application, i.e. SMA connectors for I and Q inputs and ideally K connectors for LO input and RF output. The I/Q mixer must be qualified for usage as an upconverter.

5.2 Test Measurement

5.2.1 Input

For a test measurement, we choose a simple baseband signal with 16QAM digital modulation at 4 Msym/s. The LO carrier frequency is set to 22 GHz (continuous wave). In summary, the test scenario input parameters are as follows:

Input parameters		
R&S®SMF100A	LO power	17 dBm
	LO frequency	22 GHz
R&S®AFQ100A	IF or I/Q level	0 dBm
	IF or I/Q frequency	DC (0 Hz)
	IF or I/Q bandwidth	4 MHz
	Modulation	16QAM, 4 Msym/s

Fig. 4 shows the LO input signal (R&S®SMF100A) demonstrating excellent spectral purity.

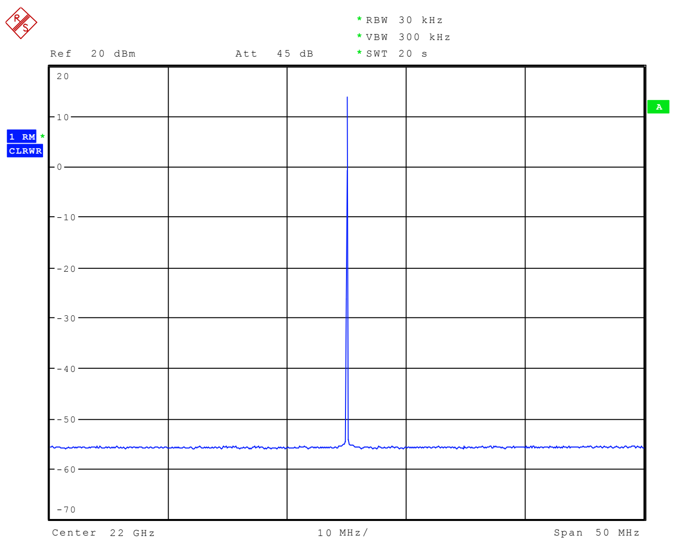


Fig. 4: Frequency spectrum of the 22 GHz LO input signal.

5.2.1.1 How to set the IF or I/Q level?

The IF or I/Q level depends on two values: the amplitude level of the I/Q signal and the crest factor of the waveform. Both values are displayed on the graphical user interface of the instrument (Fig. 5).

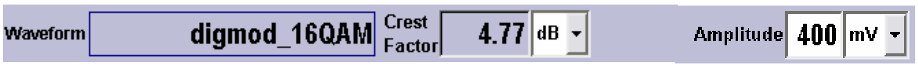


Fig. 5: Detail of the graphical user interface of the AFQ

If the amplitude is set to e.g. 400 mV, then the I/Q signal has a peak voltage of 400 mV (unbalanced analog output). A voltage of 400 mV corresponds to 5 dBm in a 50 Ω system. The PEP value (5 dBm in this example) minus the crest factor of the waveform gives the rms level for the I/Q signal. With a crest factor of e.g. 5 dB, the rms level would be 0 dBm. Thus, the IF or I/Q level (rms) would be 0 dBm in this example (Fig. 6).

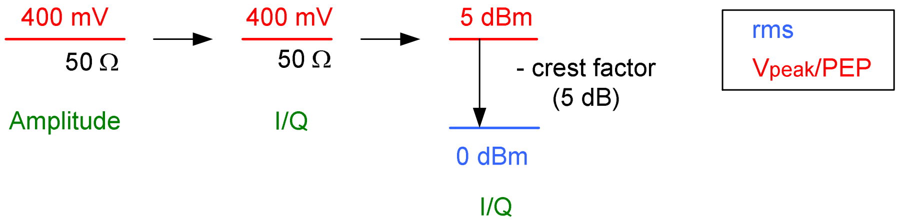


Fig. 6: Calculation of the IF or I/Q level (rms) for the AFQ.

Therefore, the amplitude (in volts) required to give a certain I/Q level (rms) can be calculated with the following formulas:

PEP [dBm] = wanted rms I/Q level [dBm] + crest factor [dB]

Amplitude_A = $\sqrt{0.05 \cdot 10^{PEP/10dBm}}$ (unbalanced output)

The R&S®AFQ100B can only be operated with balanced analog output. The I and Q outputs are connected to the I/Q mixer, the $\overline{I}$ and $\overline{Q}$ outputs are not used and terminated with 50 Ω. Therefore, the required amplitude (in volts) is twice the amplitude of the AFQA (unbalanced analog output).

Amplitude_B = $2 \cdot \sqrt{0.05 \cdot 10^{PEP/10dBm}}$ (balanced output)

Note that there is an upper limit and a lower limit on the I/Q level that can be fed into the IF or I/Q input of the mixer. The upper limit is due to compression and intermodulation distortion [1]. As long as the input power is low enough such that the mixer operates in its linear regime, the vector accuracy of the RF output signal will be good. At a certain I/Q input level the mixer will start to compress the signal. From this point on the vector accuracy of the RF signal will suffer, since signal peaks will be clipped. To avoid this, the PEP value of the I/Q input signal should be held well below the specified 1dB-compression point of the mixer. Besides compression, also intermodulation distortion plays an important role for multi-tone and multi-carrier signals (see section 6.3 for details). This factor additionally poses an upper limit on the usable I/Q input level.

There is also a lower limit on the I/Q level, however it's not a hard limit in the strict sense. In case the I/Q level is lowered continuously, the level of the RF signal reduces accordingly. By contrast, the level of the LO leakage remains fixed for a certain LO frequency, because the LO input level is fixed. Thus, at some point the level difference between the RF signal and the LO leakage won't be satisfactory any longer. The effectively usable I/Q level is hence limited.

The limited I/Q input range defines the dynamic range for the RF output signal. For example, the I/Q mixer used in this test setup yields a RF dynamic range of about 25 dB at 22 GHz.

5.2.2 Output

5.2.2.1 Spectrum

The RF output spectrum is illustrated in Fig. 7 and Fig. 8. The figures show the resulting I/Q-modulated microwave signal at 22 GHz. In Fig. 7 the frequency span is 10 GHz (16.5 GHz -26.5 GHz). Note that the RF spectrum is free of unwanted mixing products (spurious signals). Therefore, filtering of the RF signal is not required. In Fig. 8 the frequency span is reduced to 40 MHz to show the I/Q-modulated RF signal in greater detail.

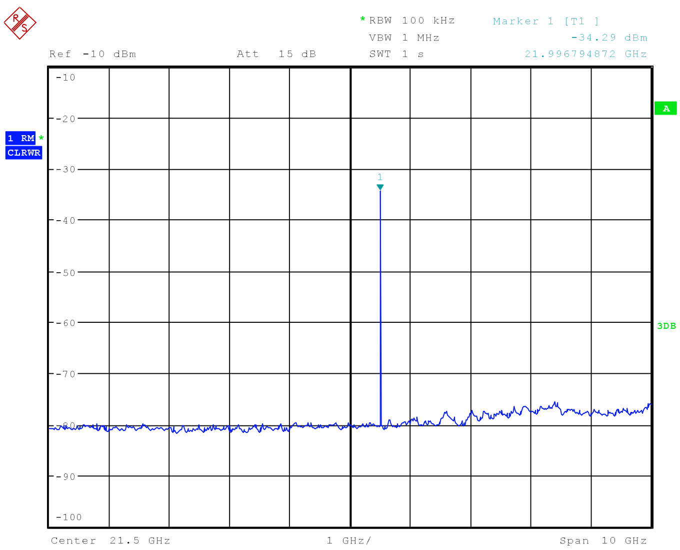


Fig. 7: Frequency spectrum of the vector-modulated microwave signal at 22 GHz. The frequency span is 10 GHz.

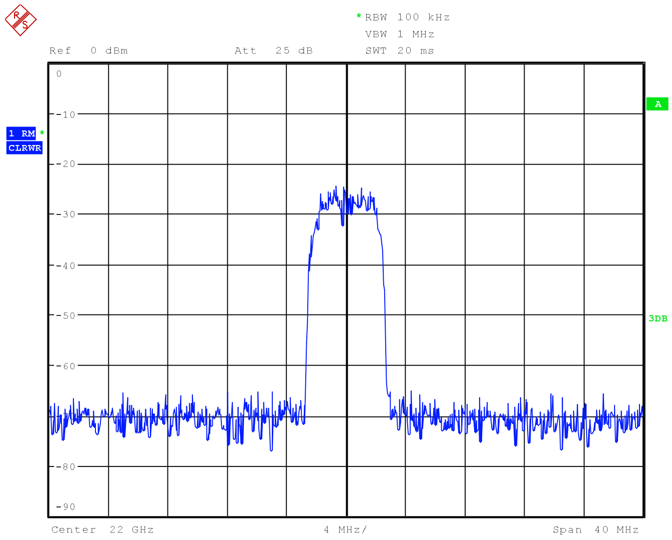


Fig. 8: Frequency spectrum of the vector-modulated microwave signal at 22 GHz. The frequency span is 40 MHz.

5.2.2.2 RF Level

The measured RF channel power is lower than the I/Q input level due to cable losses and the conversion loss of the mixer. The RF level is set via the I/Q level. The LO level remains fixed. When adjusting the I/Q level, the conversion loss needs to be taken into account to obtain the desired RF level. The achievable RF level accuracy depends on how accurate the conversion loss is known. Note that the conversion loss is a frequency-dependent quantity [1]. The following formulas show how to calculate the required amplitude (in volts) on the AFQ to obtain a certain RF level (rms) at the mixer's output.

PEP [dBm] = wanted rms RF level [dBm] – conversion loss [dB] + crest factor [dB]

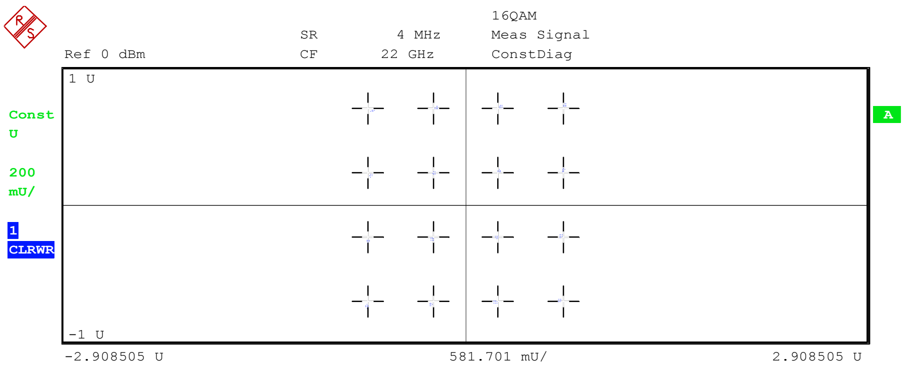
Amplitude_A = $\sqrt{0.05 \cdot 10^{PEP/10dBm}}$ (unbalanced output)

In the above formula the conversion loss is a negative value, e.g. -7dB. This calculation can be done easily by using the calculation tool, which comes with this Application Note (see section 5.2.3 for details).

As already mentioned above, the RF level is limited to a certain dynamic range due to the limited I/Q input level. Within this dynamic range the RF level is adjusted by varying the I/Q level. If the application requires RF levels that lie outside the dynamic range, additional components have to be used. For lower RF levels suitable attenuators have to be connected to the RF output of the I/Q mixer, for higher RF levels appropriate amplifiers have to be used.

5.2.2.3 EVM

The LO carrier and the sideband are suppressed; however, they overlay with the wanted modulated signal and thus cause interference. One way to quantify the quality of the modulation is to perform an error vector magnitude (EVM) measurement. The error vector is the vector between the ideal constellation point in the I/Q-plane and the actual point received. Its length (or magnitude), defined as the Euclidean distance between the two points, is the EVM. It is a measure of the modulation accuracy. Fig. 9 shows the EVM measurement performed using a spectrum analyzer.



16QAM

FILT SR 4 MHz Sym&Mod Acc

Ref 0 dBm CF 22 GHz

1 CLRWR

Att 25 dB

B

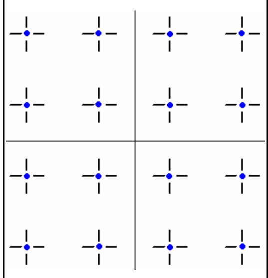
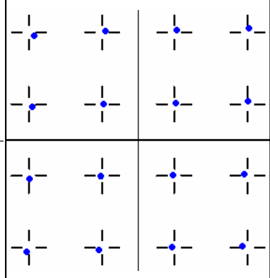
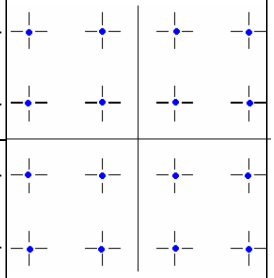
MODULATION ACCURACY				
	Result	Peak	atSym	Unit
EVM	3.280	5.911	742	%
Magnitude Err	2.008	4.318	495	%
Phase Error	1.16	-2.62	137	deg
CarrierFreq Err	307.69			Hz
Ampt Droop	-0.01			dB
Origin Offset	-32.31			dB
Gain Imbalance	0.21			dB
Quadrature Err	-3.34			deg
RHO	0.998924			
Mean Power	-11.47	-5.28	539	dBm
SNR (MER)	29.68			dB

SYMBOL TABLE (Hexadecimal)	
00000	5 7 9 7 7 0 3 9 D 2 7 A E A 2 4 3 3
00018	8 5 E D 9 A 1 D E 1 F F 0 7 B E 2 E
00036	6 4 1 2 9 D A 3 C F 9 B 1 5 2 3 8 D
00054	A B 8 9 8 8 8 0 4 2 3 0 9 C A B 0 D
00072	E 9 B 9 1 4 2 B 4 F D 9 2 5 B F 2 6
00090	A 6 6 0 3 1 9 4 6 9 7 F 4 5 8 E B 2
00108	C F 1 F 7 4 1 A D B B 0 5 A F A A 8
00126	1 4 A F 2 E E 0 7 3 A 4 F 5 D 4 4 8
00144	6 7 0 B D B 3 4 3 B C 3 F E 0 F 7 C
00162	5 C C 8 2 5 3 B 4 7 9 F 3 6 2 A 4 7
00180	1 B 5 7 1 3 1 1 0 0 8 4 6 1 3 9 5 6
00198	1 B D 3 7 2 2 8 5 6 9 F B 2 4 B 7 E
00216	4 D 4 C C 0 6 3 2 8 D 2 F E 8 B 1 D

Fig. 9: EVM measurement of the vector-modulated microwave signal.

The measured EVM of the vector modulated signal is 3.3 %. The EVM result is a consequence of the interference effects caused by the unwanted sideband. The better the specified sideband rejection of the I/Q mixer, the better the EVM result. Generally, the higher the RF operation range of the mixer, the lower the specified sideband rejection. Section 6.2 describes how the EVM result can be significantly improved.

Side note: If the IF signal has a finite frequency (i.e. nonzero IF or I/Q frequency), the wanted signal will be spectrally separated from the unwanted signals like in the case of conventional mixers. As a result, the EVM result improves. For this test setup introducing a nonzero IF frequency (e.g. 10 MHz) yields an EVM of only 0.6 % for the wanted sideband. For comparison, the measured EVM of the baseband signals I and Q is 0.25 % (no upconversion to RF). The table below summarizes the different results.

EVM results			
	I/Q baseband	**I/Q mixer**	**I/Q mixer with frequency offset**
Constellation diagram			
EVM	0.25 %	3.3 %	0.6 %

5.2.2.4 LO Leakage

The RF-to-LO isolation of the I/Q mixer is an important parameter, since it specifies how much the LO signal will leak into the RF signal. A good isolation is crucial, since the LO leakage peak overlays with the wanted modulated signal degrading signal quality. The used I/Q mixer has a RF-to-LO isolation of 40 dB. This sounds a lot, however one has to keep in mind that the I/Q mixer requires a very high LO drive power. The LO input level is 17 dBm, thus the LO leakage signal will have a level of -23 dBm. Although a relatively high LO leakage level is not uncommon for I/Q mixers, it may be a severe disturbance. Section 6.2 describes how the LO leakage can be reduced. Besides the internal LO-to-RF leakage of the I/Q mixer, the LO signal can also leak via the air into the RF signal in case an unshielded device is used (i.e. chip mounted on evaluation board). To avoid this, a suitable RF absorber (e.g. rubber sheet absorber) can be used to shield the I/Q mixer.

5.2.2.5 ACLR

Fig. 10 shows a measurement of the adjacent channel leakage ratio. The result is an ACLR of -60 dB for the adjacent channel, i.e. low but noticeable.

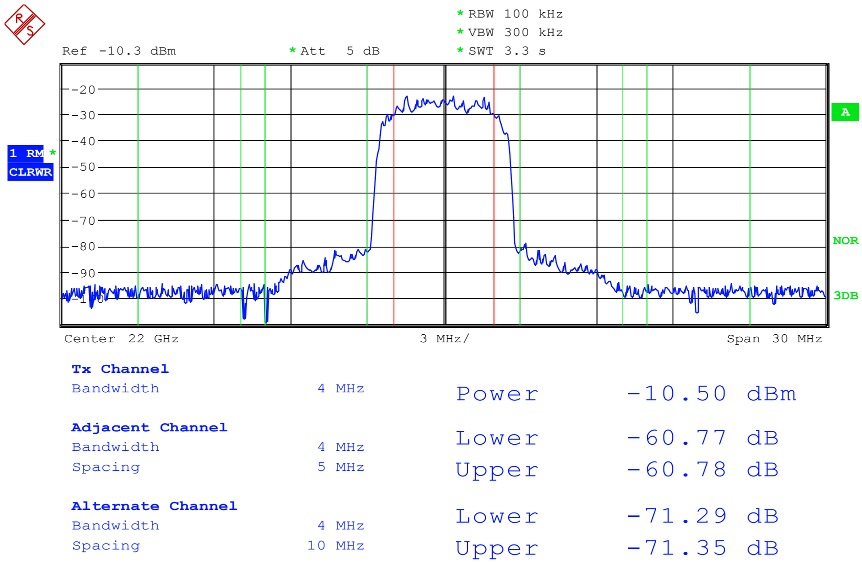


Fig. 10: ACLR measurement of the vector-modulated microwave signal.

5.2.3 Calculator Tool

This Application Note comes with a little calculation tool called "IQ Level Calculator" (Fig. 11) which facilitates setting the RF level. The software calculates the I/Q level (in volts) that is required to obtain a certain RF level at the output of the I/Q mixer. It thus helps setting the RF level. The necessary I/Q level can be adjusted on the instrument remotely via the software tool.

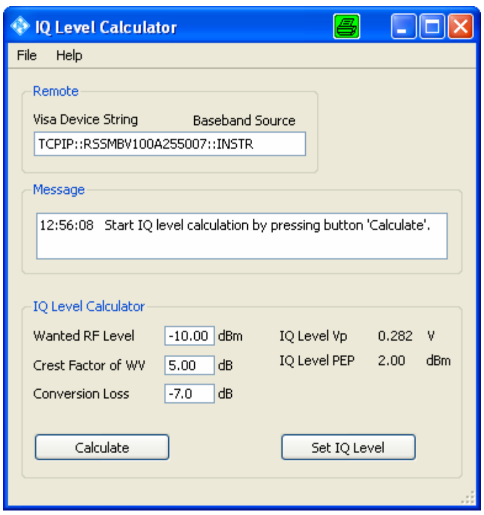


Fig. 11: Graphical user interface of the program IQ Level Calculator (V1.0.0).

Requirements for remote control

- PC (operating system: Microsoft Windows or Linux) with LAN or GPIB.
- VISA library.
- R&S® baseband source (the following generators are supported: R&S®AFQ100A, R&S®AFQ100B, R&S®SMBV100A, R&S®SMU200A, R&S®SMATE200A, R&S®SMJ100A).

Preparation

- Optionally: Plug the PC to the baseband source using LAN or GPIB cable.
- Start the application tool on the PC and configure the following input parameters.

Parameters

- Wanted RF level. Enter here the wanted rms level of the modulated microwave signal (RF signal).
- Crest Factor of WV. Enter here the crest factor of the used I/Q signal (waveform).
- Conversion Loss. Enter here the conversion loss of the I/Q mixer at the used RF frequency. By convention, the conversion loss is entered as a negative value, e.g. -7dB. (Note that the conversion loss is a frequency-dependent quantity [1].)

Optionally:

- Visa Device String for remote control of the baseband source.
  e.g. TCPIP::RSAFQ100B100153::INSTR or TCPIP::100.11.101.18::INSTR.

Program run

The calculation of the required I/Q level is started by pressing the button “Calculate”. This calculation does not require a connection to the instrument. The resulting I/Q level is given as a peak voltage (Vp) in volts into 50 Ω or as a peak envelope power (PEP) in dBm.

The calculated I/Q level can also be sent directly to a connected baseband source. Pressing the button “Set IQ Level” starts a new calculation of the required I/Q level. In addition, the appropriate instrument settings are made depending on the connected baseband source.

5.3 Test Setup with R&S®AFQ100B

In the test setup (Fig. 3), the R&S®AFQ100A can be replaced by the R&S®AFQ100B for generating wideband microwave signals with up to 528 MHz signal bandwidth (RF). This is possible because the used I/Q mixer is suitable for wideband applications due to its wide IF frequency range (DC – 4.5 GHz). Note that a wide IF frequency range is common for I/Q mixers. Such a wideband signal could be e.g. a multi-tone signal with 100 carriers spanning 500 MHz. This signal can be generated using the R&S®AFQ100B and is then upconverted to 25 GHz using the I/Q mixer together with the SMF as LO source. The result is a wideband microwave signal with a bandwidth of 500 MHz (Fig. 12). Note that an I/Q mixer (or in general an I/Q modulator) has a certain frequency response that will be imposed on the RF signal.

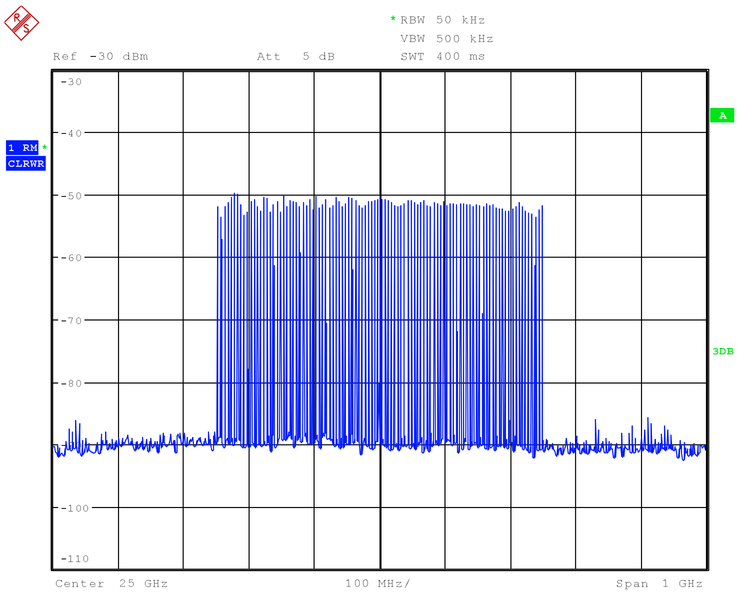


Fig. 12: Multi-tone signal at 25 GHz with a bandwidth of 500 MHz.

6 Supplementary Measurements

6.1 Baseband Offset Frequency

Normally, the applied I/Q signals have no baseband frequency offset. In case the baseband frequency offset is nonzero, the spectrum will look similar to the following example (Fig. 13). Here, the baseband signal is a 16QAM signal (1 MHz bandwidth) with a frequency offset of +20 MHz. The spectrum shows the wanted sideband, the LO leakage peak, the suppressed (lower) sideband and some additional mixing products. The wanted signal appears at $f_{LO}+f_{IF}$, i.e. it appears at an offset of +20 MHz with respect to the LO leakage peak at 22 GHz. The unwanted sideband at $f_{LO}-f_{IF}$ is rejected and exhibits a power level that is reduced by 30 dB. The remaining peaks in the spectrum correspond to mixing products at the combination frequencies $f_{LO}-3f_{IF}$, $f_{LO}-2f_{IF}$, $f_{LO}+2f_{IF}$, $f_{LO}+3f_{IF}$ and $f_{LO}+5f_{IF}$, respectively. Generally, applying a nonzero IF frequency can be used to analyze the sideband rejection and LO carrier suppression of the I/Q mixer.

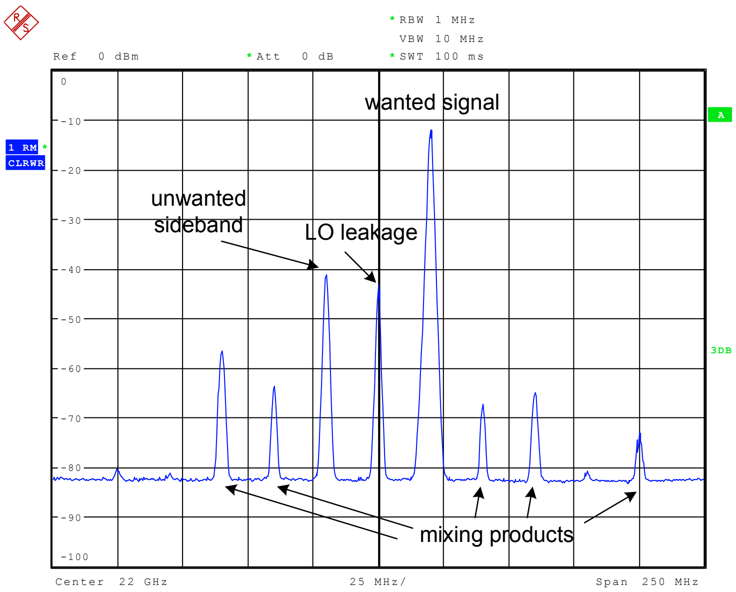


Fig. 13: RF frequency spectrum for an up-converted I/Q signal (16QAM) having a frequency offset of 20 MHz.

6.2 How to improve the EVM?

Using I/Q mixers with DC baseband signals (i.e. zero IF frequency) results in a degraded EVM performance, since the unwanted signals interfere with the wanted signal. However, the EVM result can be improved by

- compensating I/Q phase mismatches,
- compensating I/Q gain mismatches,
- varying the LO power.

The suppression of the unwanted sideband can be improved by compensating possible I/Q phase mismatches using the AFQ. The instrument allows for adding I/Q phase differences to the baseband signals. For demonstration we use the same test signal as in section 6.1. Fig. 14a shows the upper and lower sideband of the original signal, while Fig. 14b shows the same signal but with an inserted phase difference. In this example, the best sideband suppression is achieved with a phase difference of -4.0 deg. The channel power of the unwanted signal decreases from -39.9 dBm to -51.4 dBm. The sideband rejection is thus improved by an additional 11.5 dB.

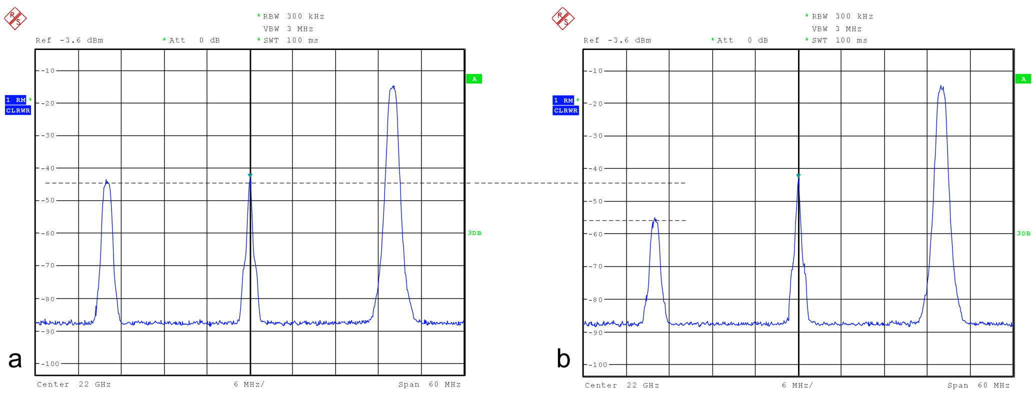


Fig. 14: RF frequency spectrum showing the sideband rejection of the original IF signal (a) and of the IF signal with applied I/Q phase difference (b).

A suitable I/Q phase difference can easily be found by varying the applied phase difference and monitoring the effect on the sideband suppression. This way, the suppression can be iteratively maximized.
The phase difference is set in the Impairments block of the AFQ:

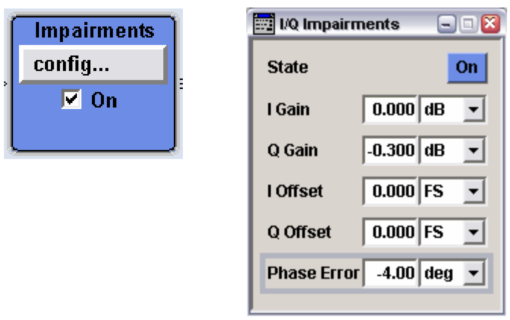


Fig. 15: I/Q Impairments block and Impairments configuration menu of the AFQ.

The suppression of the unwanted sideband can be improved even further by compensating possible I/Q gain mismatches. A suitable I/Q gain imbalance can be set in the Impairments block of the AFQ (Fig. 15). In this example, the best sideband suppression is achieved with a gain imbalance of -0.3 dB. The channel power of the unwanted signal decreases from -51.4 dBm to -63.7 dBm. Hence, the inherent sideband rejection of the mixer is improved by 23.8 dB in total (Fig.16).

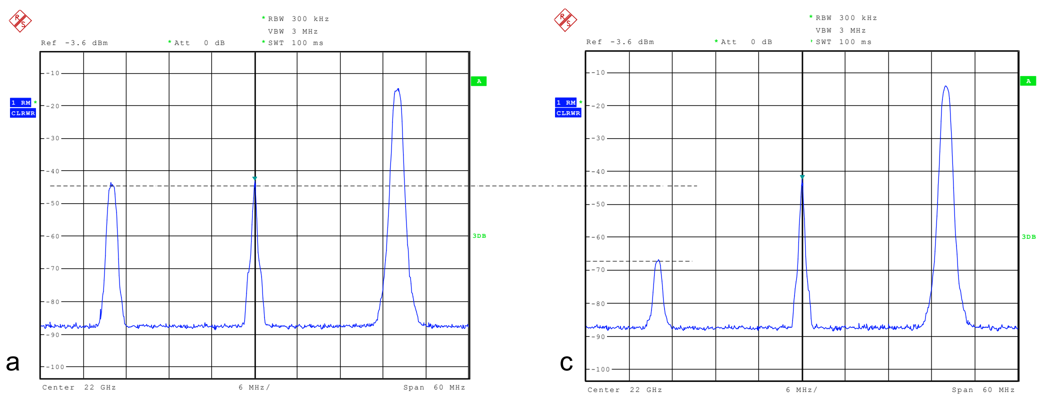


Fig. 16: RF frequency spectrum showing the sideband rejection of the original IF signal (a) and the IF signal with applied I/Q phase difference and I/Q gain imbalance (c).

Varying the applied LO power can also positively influence the EVM result. In this example, raising the LO power beyond a level of 17 dBm degrades the EVM performance slightly, while lowering the LO level results in a notable improvement.

In the following we compare several EVM measurements performed with a 16QAM test signal (bandwidth is 1 MHz). First, the EVM of the pure I/Q baseband signals is analyzed. The measured EVM is only 0.27 %. In a next step, the baseband signals of the AFQ are upconverted using the I/Q mixer. In addition, a baseband frequency offset of 20 MHz is introduced (i.e. IF frequency is 20 MHz). The measured EVM of the wanted signal at 22.02 GHz is 0.45 %. To now analyze the influence of the unwanted signals on the EVM, the frequency offset is removed (i.e. IF frequency is 0 MHz). As a consequence, the EVM increases up to 4.6 % for the wanted signal at 22.00 GHz. This result can be improved significantly by applying I/Q phase and I/Q gain impairments to the baseband signals in order to compensate the measured I/Q mismatches (Fig. 17).

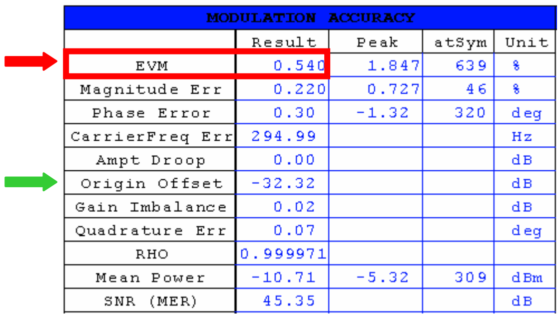
MODULATION ACCURACY				
	Result	Peak	atSym	Unit
EVM	4.611	7.490	101	%
Magnitude Err	2.799	5.032	389	%
Phase Error	1.67	3.30	203	deg
CarrierFreq Err	294.09			Hz
Ampt Droop	0.01			dB
Origin Offset	-30.43			dB
Gain Imbalance	0.39			dB
Quadrature Err	-4.53			deg
RHO	0.997874			
Mean Power	-10.59	-4.83	445	dBm
SNR (MER)	26.72			dB

Fig. 17: Measured EVM result for the upconverted 16QAM test signal. The measured I/Q mismatches are highlighted.

Introducing a suitable phase difference (-4.0 deg) yields an EVM of 2.0 % for the modulated microwave signal. Additionally, applying a suitable gain imbalance (-0.39 dB) yields an EVM of 0.6 %. Finally, lowering the LO power by 0.7 dB, i.e. from 17 dBm to 16.3 dBm, yields an EVM of only 0.5 %. The following table summarizes the measured EVM results.

EVM results					
EVM	**Signal**	**IF frequency**	**LO power**	**Phase offset**	**Gain imbalance**
0.27 %	Baseband I/Q	0 MHz	---	0 deg	0 dB
0.45 %	RF with frequency offset	20 MHz	17 dBm	0 deg	0 dB
4.6 %	RF standard	0 MHz	17 dBm	0 deg	0 dB
2.0 %	RF with I/Q phase error	0 MHz	17 dBm	-4.0 deg	0 dB
0.6 %	RF with I/Q phase error and I/Q gain imbalance	0 MHz	17 dBm	-4.0 deg	-0.39 dB
0.5 %	RF with I/Q phase error, I/Q gain imbalance, and reduced LO power	0 MHz	16.3 dBm	-4.0 deg	-0.39 dB

These test measurements clearly demonstrate that the EVM performance of I/Q mixers driven with DC baseband signals can be significantly improved. The EVM values that can be achieved are very well acceptable for vector-modulated signals in the microwave frequency range.



MODULATION ACCURACY	Result	Peak	atSym	Unit
EVM	0.540	1.847	639	%
Magnitude Err	0.220	0.727	46	%
Phase Error	0.30	-1.32	320	deg
CarrierFreq Err	294.99			Hz
Ampt Droop	0.00			dB
Origin Offset	-32.32			dB
Gain Imbalance	0.02			dB
Quadrature Err	0.07			deg
RHO	0.999971			
Mean Power	-10.71	-5.32	309	dBm
SNR (MER)	45.35			dB

Fig. 18: Measured EVM result for the upconverted 16QAM test signal with applied I/Q phase and I/Q gain impairments.

The result for the measured I/Q offset (i.e. Origin Offset, see Fig. 18) can be improved by applying I/Q offsets to the baseband signals (Impairments block of AFQ). This leads to a suppression of the LO component in the RF signal. In this example, a Q offset of -0.006 Full Scale (FS) yields an additional suppression of the LO leakage peak by 24 dB. The measured origin offset decreases from -32 dB (no Q offset) to -56 dB (Q offset is -0.006 FS).

6.2.1 I/Q Mismatch Compensation – Step-by-Step Procedure

The I/Q mismatch compensation requires a spectrum analyzer and can be done either

- manually on the basis of the frequency spectrum

or

- manually by means of a vector signal analysis option

The advantage of the first method is that no vector signal analysis option is needed on the analyzer. However, the second method is strongly recommended, since it is much more precise and less time-consuming.

6.2.1.1 Frequency Spectrum Method

- Apply a baseband frequency offset to the I/Q signals, e.g. 20 MHz.
- Watch the RF frequency spectrum while varying the I/Q Impairments on the AFQ.
- Minimize the unwanted sideband by gradually varying "Q Gain" of the I/Q Impairments (AFQ). If the sideband solely increases, set "Q Gain" back to zero and gradually vary "I Gain" of the I/Q Impairments (AFQ).
- Minimize the unwanted sideband further by gradually varying "Phase Error" of the I/Q Impairments (AFQ). Note that the parameter "Phase Error" can be set to positive and negative values.

Optionally:

- Minimize the LO leakage peak by gradually varying "Q Offset" of the I/Q Impairments (if "Q Gain" is nonzero) or "I Offset" (if "I Gain" is nonzero).

  Note that for the AFQ the parameters "Q Offset" and "I Offset" can only be set, if the corresponding parameter "Q Gain" or "I Gain" is nonzero. The accessible data range of "I/Q Offset" depends on the setting made for "I/Q Gain". If necessary, the suppression of the LO leakage can be improved by lowering both parameters "Q Gain" and "I Gain" by a constant value (e.g. 0.4 dB). Now, the LO leakage can be further minimized by gradually varying "Q Offset", then gradually varying "I Offset" and finally gradually varying "Q Offset" again.

- Remove the applied baseband frequency offset.

6.2.1.2 Vector Analysis Method

- Use a vector signal analysis option (e.g. R&S®FSQ-K70) to demodulate and analyze the RF signal as show in Fig. 17.

  (If the analyzer is not able to synchronize to the RF signal although all analyzer settings (e.g. RF frequency, modulation/general settings, demodulation settings, etc.) are set correctly, this could be due to high LO leakage. In this case, one can either reduce the LO leakage using the frequency spectrum method (as described above) prior to the measurement or use an RF absorber to cover an unshielded I/Q mixer to prevent leakage via the air.)

- Read off the measured value for “Gain Imbalance”.
- Enter this value into “Q Gain” of the I/Q Impairments (AFQ). If the measured value on the analyzer worsens, set “Q Gain” back to zero and enter the originally measured value into “I Gain” of the I/Q Impairments (AFQ).
- Read off the measured value for “Quadrature Err”.
- Enter this value into “Phase Error” of the I/Q Impairments (AFQ). If the measured value on the analyzer worsens, change the sign of the entered value.

Optionally:

- Minimize the measured value for “Origin Offset” by gradually varying “Q Offset” of the I/Q Impairments (if “Q Gain” is nonzero) or “I Offset” (if “I Gain” is nonzero).

6.2.2 I/Q Mismatch Compensation – Validity

The question is: Does the I/Q mismatch compensation hold, if

- the I/Q level,
- the waveform,
- the RF frequency

is changed?

I/Q Level

The I/Q mismatch compensation holds, if the I/Q level is varied within the usable input range (see section 5.2.1 for details on the input range).

Waveform

The I/Q mismatch compensation also holds, if the waveform is changed. Independent of the waveform and the associated crest factor the I/Q mismatch compensation remains valid.

RF Frequency

The I/Q mismatch compensation does not hold, if the RF frequency changes. In this case, the I/Q mismatch compensation has to be repeated. Only for small variations of the RF frequency (i.e. <0.1 GHz) the I/Q mismatch compensation still holds.

6.3 Multicarrier

When the baseband signal is a multicarrier signal, the I/Q mixer will generate intermodulation products which lead to distortion of the upconverted signal [1]. As a test signal we use a WLANg OFDM signal (54 Mbps, 64QAM). Fig. 19 compares the EVM results of two identical test signals (22 GHz). The only difference between the two cases is the applied IF input power (i.e. I/Q input level): 0 dBm PEP in the first case and 5 dBm PEP in the second case. The measured EVM increases as the IF input power rises due to the strongly increasing intermodulation products, which deteriorate the modulation accuracy.

IEEE 802.11g				Test signal	
Frequency:	22 GHz	Ref Level:	-5 dBm	External Att:	0 dB
Sweep Mode:	Continuous	Trigger Mode:	Free Run	Trigger Offset:	-10 µs
Preamble Type:	OFDM	Modulation:	54 Mbps 64 QAM	PSDU Data Length:	1/1366

Result Summary						IF power: 0 dBm PEP
No. of Bursts	6					
	Min	Mean	Limit	Max	Limit	Unit
EVM All Carriers	**2.16**	**2.18**	5.62	**2.22**	5.62	%
	- 33.31	**- 33.24**	- 25.00	**- 33.06**	- 25.00	dB

Result Summary						IF power: 5 dBm PEP
No. of Bursts	7					
	Min	Mean	Limit	Max	Limit	Unit
EVM All Carriers	**3.14**	**3.17**	5.62	**3.21**	5.62	%
	- 30.06	**- 29.97**	- 25.00	**- 29.87**	- 25.00	dB

Fig. 19: EVM result of WLANg signals with different IF input powers (PEP).

To keep intermodulation distortion low for multicarrier signals the IF input level (i.e. I/Q input level) should be kept well below the specified intercept point of the mixer.

7 Alternative Test Setup

7.1 Test Setup

The I/Q signals are provided by the signal generator R&S®SMBV100A. Fig. 20 shows the test configuration.

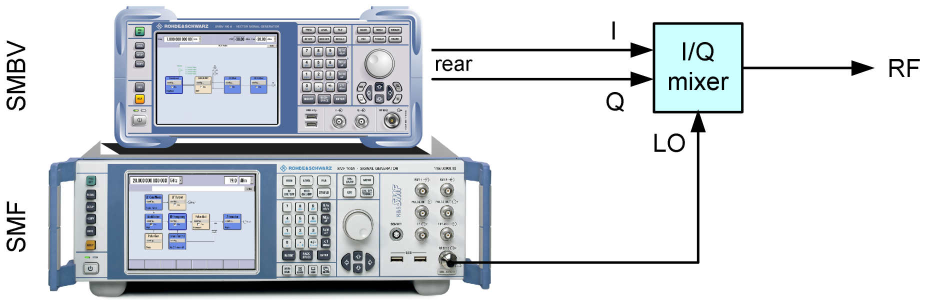


Fig. 20: Schematic of the test setup for vector signal generation using an I/Q mixer.

The level of the I/Q signals is set via the “Analog I/Q Output Settings” menu (Fig. 21). The option “Optimize I/Q Signals For RF Output” should be disabled, and the “I/Q Output Type” should be “Single Ended”. With “Mode” set to “Variable” the output level of the baseband signals can be varied in order to adjust the IF input power.

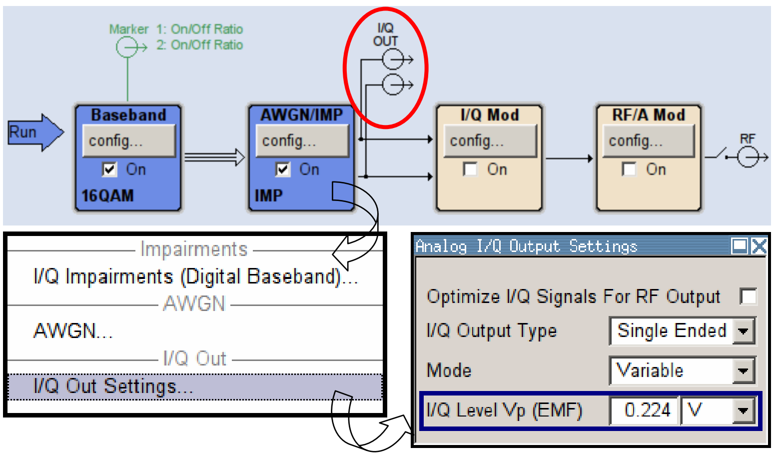


Fig. 21: Details of the graphical user interface of the SMBV showing the settings required for adjusting the IF input power.

Note that the IF or I/Q level is set in units of volts EMF. A voltage of e.g. Vp (EMF) = 800 mV corresponds to a voltage of Vp = 400 mV into 50 Ω. Thus, if the "I/Q Level Vp (EMF)" is set to 800 mV, then the I/Q signals have a peak voltage of 400 mV (single-ended analog output) into 50 Ω. This corresponds to a PEP value of 5 dBm. The rms level for the I/Q signals is given by the PEP value minus the crest factor of the waveform (e.g. 5 dB). Thus, the I/Q level (rms) would be 0 dBm in this example (Fig. 22).

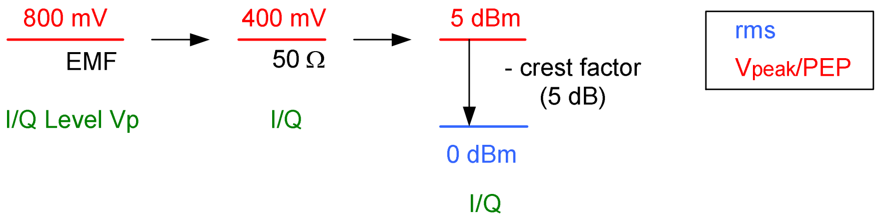


Fig. 22: Calculation of the IF or I/Q level (rms) for the SMBV.

Therefore, the "I/Q Level Vp (EMF)" in volts required to give a certain I/Q level (rms) at the input of the mixer can be calculated with the following formulas:

PEP [dBm] = wanted rms I/Q level [dBm] + crest factor [dB]

I/Q Level Vp (EMF) = $2 \cdot \sqrt{0.05 \cdot 10^{PEP/10dBm}}$ (single-ended output)

The following formulas show how to calculate the required "I/Q Level Vp (EMF)" in volts to obtain a certain RF level (rms) at the output of the mixer.

PEP [dBm] = wanted rms RF level [dBm] – conversion loss [dB] + crest factor [dB]

I/Q Level Vp (EMF) = $2 \cdot \sqrt{0.05 \cdot 10^{PEP/10dBm}}$ (single-ended output)

In the above formula the conversion loss is a negative value, e.g. -7dB. Note that the conversion loss is a frequency-dependent quantity [1]. Please read section 5.2.2.2 for more details and additional information.

The "I/Q Impairments" menu of the SMBV (Fig. 23) slightly differs from the "I/Q Impairments" menu of the AFQ (Fig. 15). The option "Optimize Internal I/Q Impairments For RF Output" should be disabled.

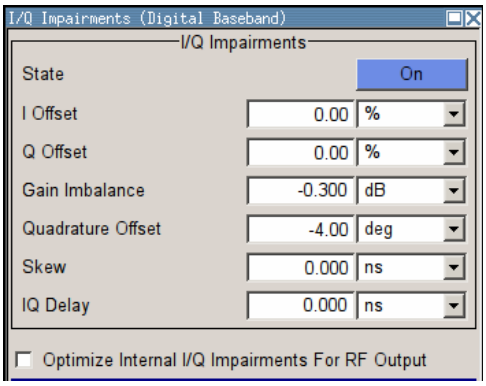


Fig. 23: I/Q Impairments configuration menu of the SMBV.

7.2 Test Measurements

7.2.1 16QAM Signal at 1 Msym/s

For this measurement we use the same test signal as in sections 6.1 and 6.2 together with the following settings.

Input parameters		
R&S®SMF100A	LO power	16.3 dBm
	LO frequency	22 GHz
R&S®SMBV100A	IF channel power	0 dBm
	Modulation	16QAM, 1 Msym/s

With a zero IF frequency, an EVM of 0.5 % is achieved by compensating the I/Q mismatches. The SMBV also allows very good LO carrier suppression, resulting in an origin offset of -71.8 dB (Fig. 24). Fig. 25 shows the test signal with a baseband frequency offset of 20 MHz to illustrate the sideband and LO suppression achieved by applying suitable I/Q offsets, gain imbalance and quadrature offset. In this example, the applied I/Q offsets are 0.45 % and -1.97 % respectively. The gain imbalance is -0.33 dB and the quadrature offset is 4.48 deg.

MODULATION ACCURACY				
	Result	Peak	atSym	Unit
EVM	0.465	1.429	322	%
Magnitude Err	0.184	0.612	653	%
Phase Error	0.26	-0.84	367	deg
CarrierFreq Err	296.26			Hz
Ampt Droop	0.00			dB
Origin Offset	-71.77			dB
Gain Imbalance	-0.00			dB
Quadrature Err	-0.04			deg
RHO	0.999978			
Mean Power	-11.30	-5.22	218	dBm
SNR (MER)	46.65			dB

Fig. 24: Measured EVM for the upconverted 16QAM test signal with applied I/Q impairments.

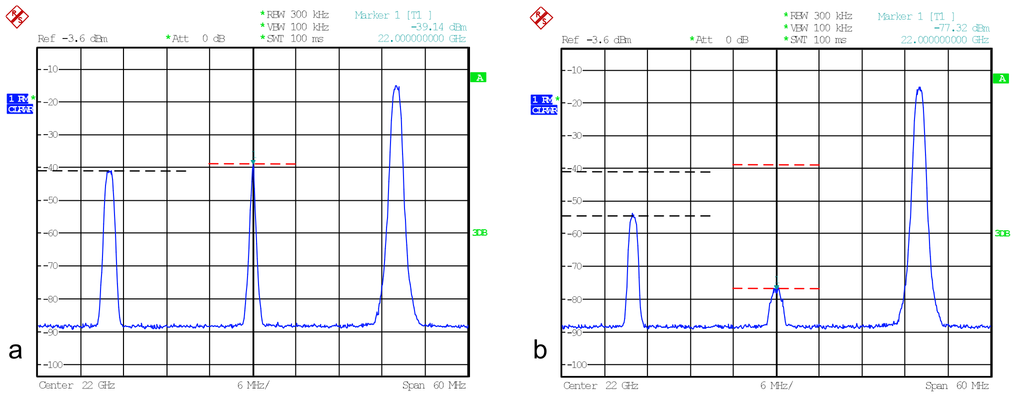


Fig. 25: RF spectrum showing the sideband and LO carrier suppression of the IF signal without (a) and with applied I/Q impairments (b).

7.2.1.1 I/Q Mismatch Compensation – Step-by-Step Procedure

The I/Q mismatch compensation requires a spectrum analyzer and can be done either

- manually on the basis of the frequency spectrum

or

- manually by means of a vector signal analysis option

The advantage of the first method is that no vector signal analysis option is needed on the analyzer. However, the second method is strongly recommended, since it is much more precise and less time-consuming.

Frequency Spectrum Method

- Apply a baseband frequency offset to the I/Q signals, e.g. 20 MHz.
- Watch the RF frequency spectrum while varying the I/Q Impairments on the SMBV.
- Minimize the unwanted sideband by gradually varying “Gain Imbalance” of the I/Q Impairments (SMBV).

- Minimize the unwanted sideband further by gradually varying “Quadrature Offset” of the I/Q Impairments (SMBV).

Optionally:

- Minimize the LO leakage peak by gradually varying “I Offset” of the I/Q Impairments (SMBV). Then, minimize the peak further by gradually varying “Q Offset”. Finally, gradually vary “I Offset” again (in finer steps) to find the absolute minimum.

- Remove the applied baseband frequency offset.

Vector Analysis Method

- Use a vector signal analysis option (e.g. R&S®FSQ-K70) to demodulate and analyze the RF signal as show in Fig. 17.
- Read off the measured value for “Gain Imbalance”.
- Enter this value into “Gain Imbalance” of the I/Q Impairments (SMBV). If the measured value on the analyzer worsens, change the sign of the entered value.
- Read off the measured value for “Quadrature Err”.
- Enter this value into “Quadrature Offset” of the I/Q Impairments (SMBV). If the measured value on the analyzer worsens, change the sign of the entered value.

Optionally:

- Minimize the measured value for “Origin Offset” by gradually varying “I Offset” of the I/Q Impairments (SMBV). Then, minimize the measured value further by gradually varying “Q Offset”. Finally, gradually vary “I Offset” again (in finer steps) to find the absolute minimum.

7.2.2 16QAM Signal at 10 Msym/s

For this measurement we use a 16QAM test signal at 10 Msym/s together with the following settings.

Input parameters		
R&S®SMF100A	LO power	16.3 dBm
	LO frequency	22 GHz
R&S®SMBV100A	IF channel power	0 dBm
	IF frequency	DC (0 Hz)
	Modulation	16QAM, 10 Msym/s

Fig. 26 shows the upconverted signal. The delta marker in the RF spectrum reads -59.4 dB at -12.0 MHz from the carrier. With I/Q mismatch compensation the measured EVM is 0.92 %.

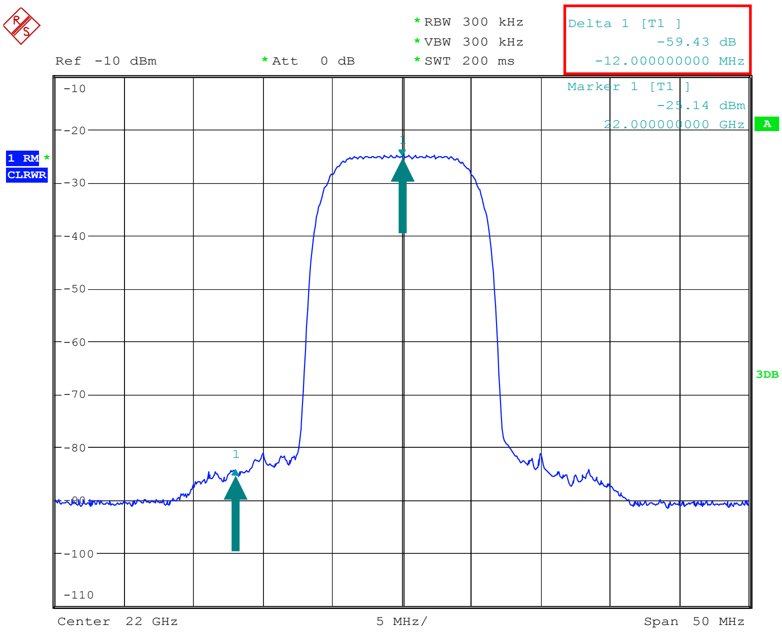


Fig. 26: RF frequency spectrum of the upconverted 16QAM test signal (10 Msym/s).

7.2.3 Two-Tone Signal

For this measurement we use a two-tone signal (carrier spacing is 10 MHz) together with the following settings.

Input parameters		
R&S®SMF100A	LO power	16.3 dBm
	LO frequency	22 GHz
R&S®SMBV100A	IF channel power	0 dBm
	IF frequency	DC (0 Hz)

Fig. 27 shows the upconverted signal with applied LO suppression (I/Q offsets are 0.39 % and -1.93 %, respectively). The delta marker in the RF spectrum reads -54.3 dB at -20.0 MHz from the second carrier.

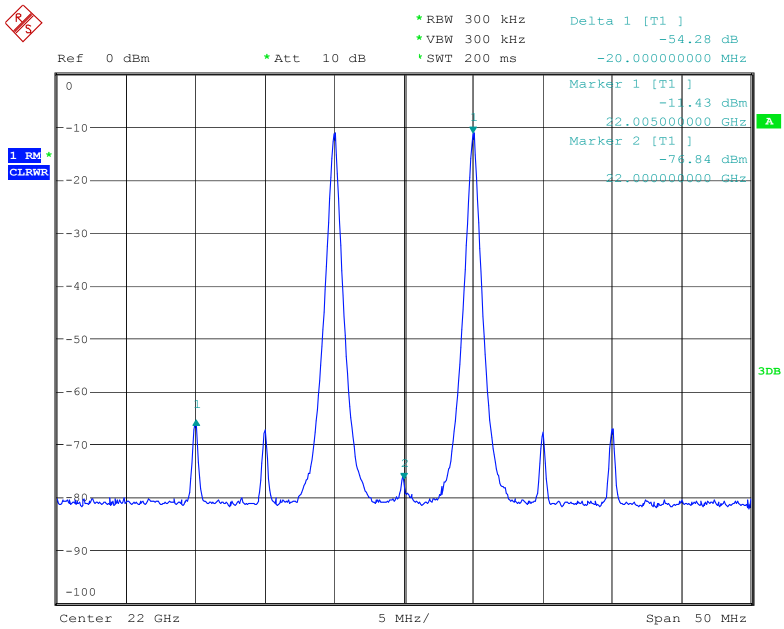


Fig. 27: RF spectrum of the upconverted two-tone signal.

7.2.4 Multi-Tone Signal

For this measurement we use a multi-tone signal (10 carriers with 1 MHz spacing) together with the same settings as in subsection 7.2.3. Fig. 28 shows the upconverted signal with applied LO suppression (I/Q offsets are 0.39 % and -1.93 %, respectively).

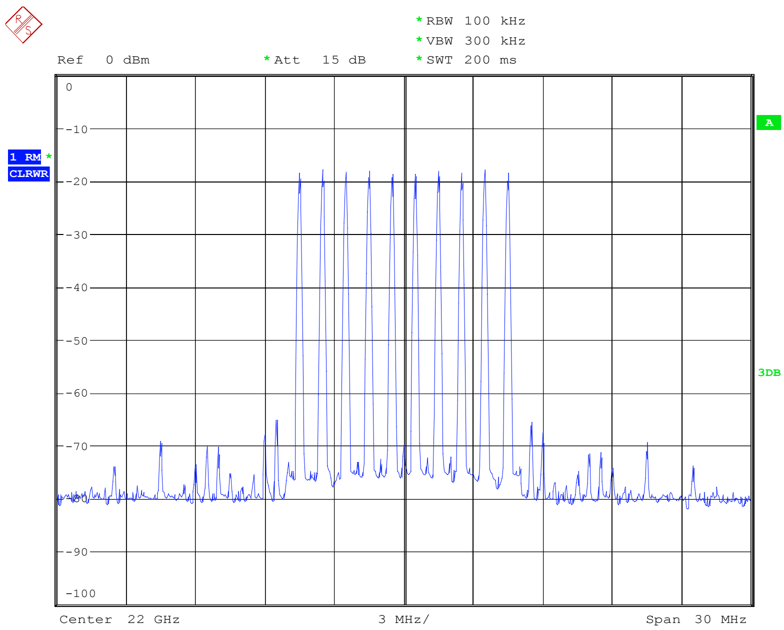


Fig. 28: RF spectrum of the upconverted multi-tone signal.

7.2.5 Image Rejection

For this measurement we use a multi-tone signal (carrier spacing is 1 MHz) together with the same settings as specified in section 7.2.3. To visualize image rejection the test signal has 50 active carriers (with negative frequency offset) and 50 disabled carriers (with positive frequency offset). Fig. 29 shows the upconverted signal with applied I/Q mismatch compensation for image suppression (gain imbalance is -0.39 dB and quadrature offset is 3.70 deg).

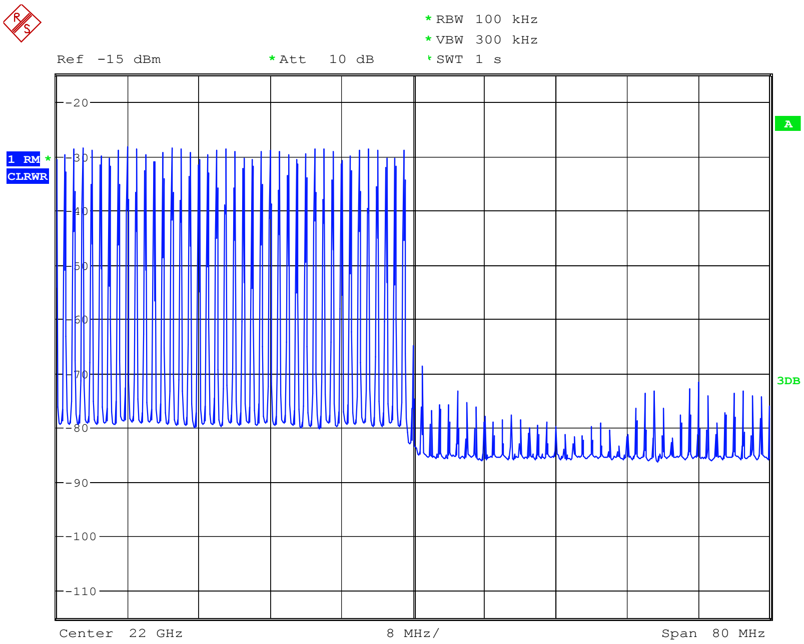


Fig. 29: RF spectrum of the upconverted multi-tone signal visualizing image rejection.

8 Summary

This application note described how to generate vector signals at microwave frequencies by means of external signal upconversion. A versatile and cost-efficient solution is to use the R&S®SMF100A microwave signal generator as a LO source for an external I/Q mixer together with a baseband signal source such as the R&S®AFQ100A. By direct upconversion of the I/Q baseband signals, vector-modulated microwave signals can be generated, exhibiting very good modulation accuracy. Furthermore, the RF spectrum can be kept free of unwanted mixing products (spurious signals), which makes the filtering of the spectrum redundant.

9 Abbreviations

ACLR	adjacent channel leakage ratio
CW	continuous wave
DC	direct current
EMF	electromagnetic force
EVM	error vector magnitude
FS	full scale
IF	intermediate frequency
LO	local oscillator
PEP	peak envelope power
QAM	quadrature amplitude modulation
RF	radio frequency
SSB	single sideband

10 References

[1] Rohde & Schwarz, Application Note 1GP65_0E, “Up-converting modulated signals to microwave with an external mixer and the R&S SMF100A”

- Basics of mixer principle
- Description of proper operation
- Application examples

[2] Data sheet I/Q mixer, Hittite Microwave Corporation
HMC524LC3B - GaAs MMIC I/Q Mixer / IRM SMT, 22-32 GHz

11 Ordering Information

R&S®SMF100A	**Microwave Signal Generator**	1167.0000.02
R&S®SMF-B122	Frequency Range 1 GHz to 22 GHz	1167.7004.03
R&S®SMF-B144	Frequency Range 1 GHz to 43.5 GHz	1167.7204.03
R&S®SMF-B1	OCXO Reference Oscillator	1167.9159.02
R&S®SMF-B2	Frequency Extension 100 kHz to 1 GHz	1167.4005.02
R&S®SMF-B20	AM/FM/φM/LOG AM Modulator	1167.9594.02
R&S®SMF-B26	Step Attenuator 100 kHz to 22 GHz	1167.5553.02
R&S®SMF-B27	Step Attenuator 100 kHz to 43.5 GHz	1176.5776.02
R&S®SMF-B32	High Output Power (without SMF-B2 installed)	1415.2304.02
R&S®SMF-B34	High Output Power (with SMF-B2 installed)	1415.2404.02
R&S®SMF-B81	Rear Connectors 22 GHz	1167.5999.02
R&S®SMF-B82	Rear Connectors 43.5 GHz	1167.6208.02
R&S®SMF-B83	Removable GPIB	1167.6408.02
R&S®SMF-B84	Removable USB	1167.6608.02
R&S®SMF-B85	Removable Flash Disk	1167.6808.02
R&S®SMF-K3	Narrow Pulse Modulation	1167.7804.02
R&S®SMF-K4	Ramp Sweep	1167.7604.02
R&S®SMF-K23	Pulse Generator	1167.7704.02
R&S®SMF-K27	Pulse Train	1415.2004.02
R&S®SMF-K28	Power Analysis	1415.2104.02

R&S®AFQ100A	**I/Q Modulation Generator**	1401.3003.02
R&S®AFQ-B10	Waveform Memory 256 Msample	1401.5106.02
R&S®AFQ-B11	Waveform Memory 1 Gsample	1401.5206.02

R&S®SMBV100A	**Vector Signal Generator**	1407.6004.02
R&S®SMBV-B103	9 kHz to 3.2 GHz	1407.9603.02
R&S®SMBV-B106	9 kHz to 6 GHz	1407.9703.02
R&S®SMBV-B1	Reference Oscillator OCXO	1407.8407.02
R&S®SMBV-B90	Phase Coherence	1407.9303.02
R&S®SMBV-K22	Pulse Modulator	1415.8019.02
R&S®SMBV-K23	Pulse Generator	1415.8025.02
R&S®SMBV-B10	Baseband Generator with Digital Modulation (realtime) and ARB (32 Msample), 120 MHz RF Bandwidth	1407.8607.02
R&S®SMBV-B50	Baseband Generator with ARB (32 Msample), 120 MHz RF bandwidth	1407.8907.02
R&S®SMBV-B51	Baseband Generator with ARB (32 Msample), 60 MHz RF bandwidth	1407.9003.02
R&S®SMBV-B55	Memory Extension for ARB to 256 Msample	1407.9203.02
R&S®SMBV-K18	Digital Baseband Connectivity	1415.8002.02

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