Start Time: March 6, 2024 | 4:30 PM CET | 7:30 AM PST | 10:30 AM EST

Spread Spectrum to Reduce EMI

Florian Seliger, Monolithic Power Systems

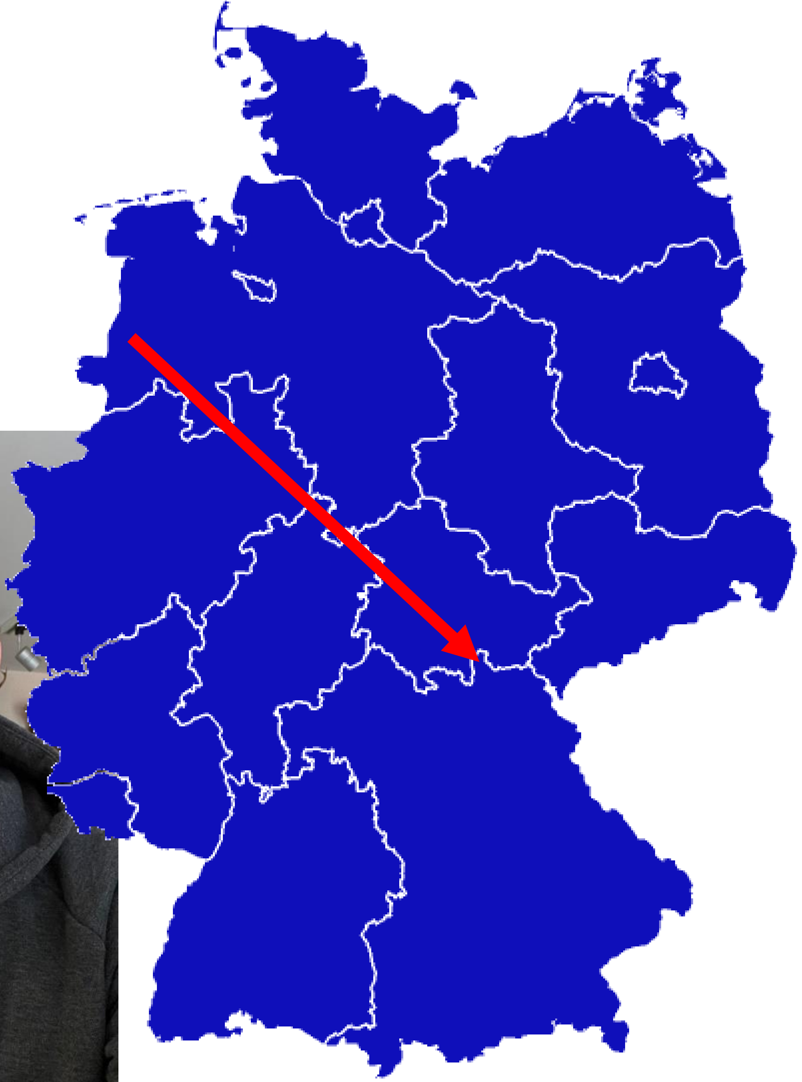
March 2024

Agenda

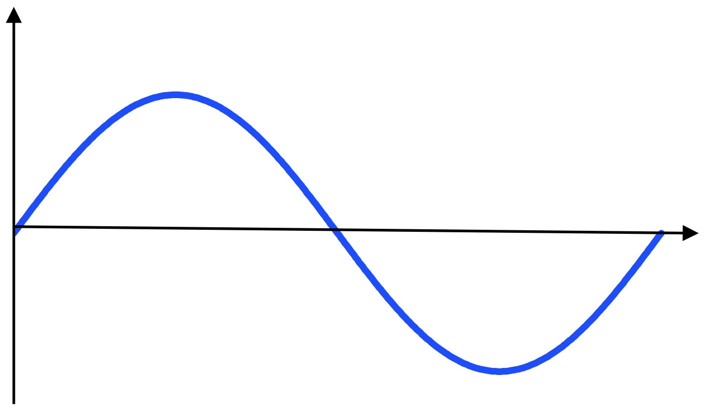
- Spectrum of a Traditional Switched-Mode Power Supply (SMPS)
- Theory behind Frequency Spread Spectrum (FSS)
- Practical Measurements on Real Boards Benefits
- Practical Measurements with EMI Receiver
- Limitations of Frequency Spread Spectrum
- Conclusion
- Q&A

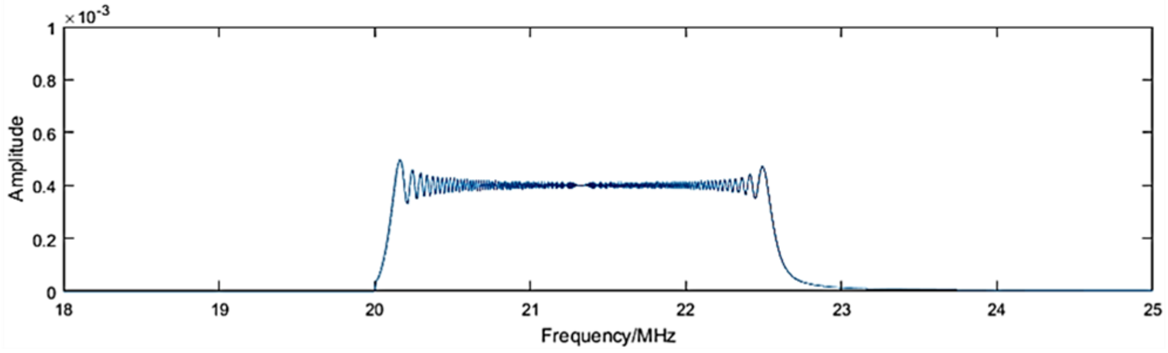
Florian Seliger

- 30 years old
- from Kronach, Germany
- Married
- Field Applications Engineer at MPS
- 1 son and 1 dalmatian dog



Spectrum of a Traditional Switched-Mode Power Supply (SMPS)

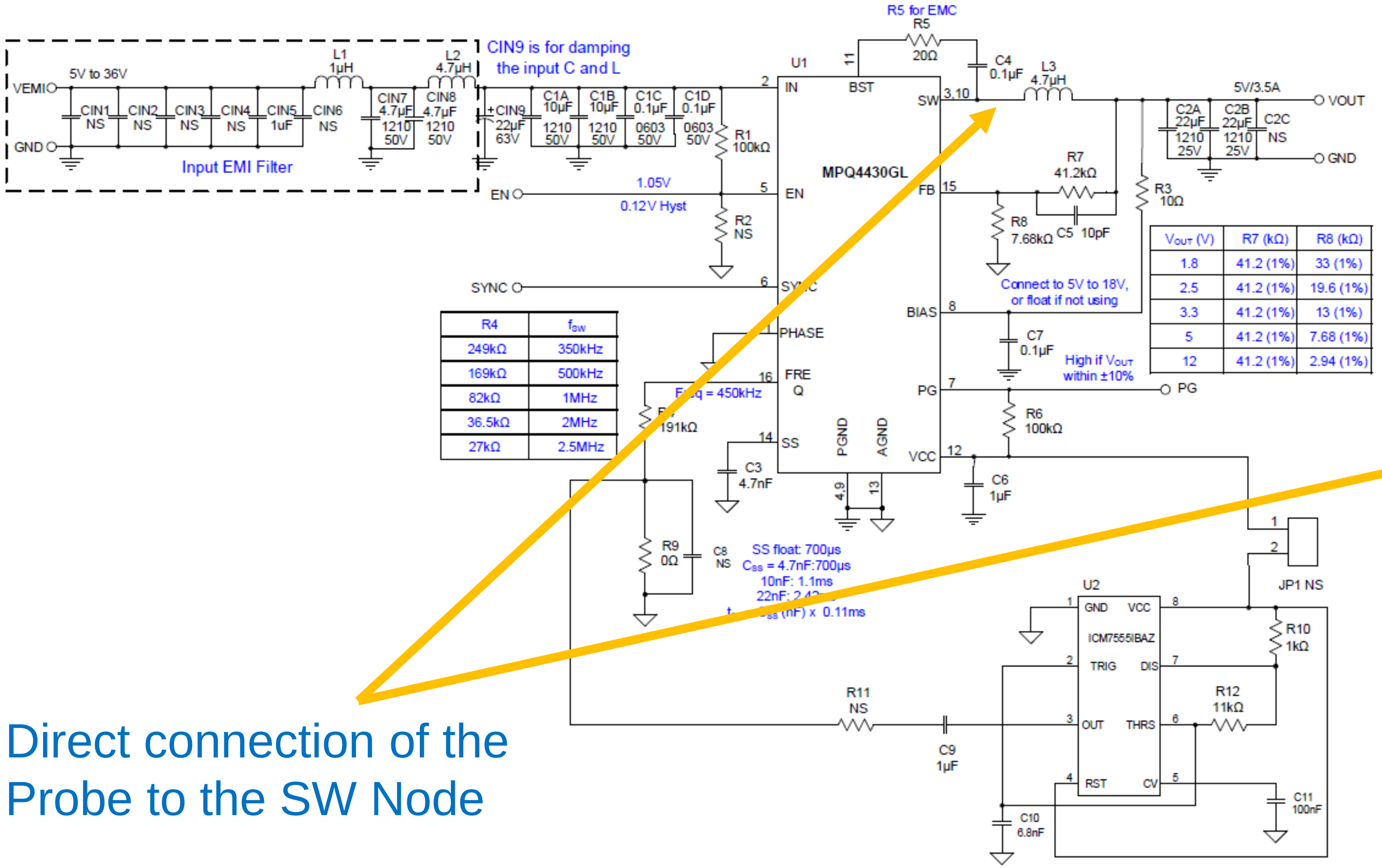




Spectrum of a Traditional SMPS

EVQ4430-L-00A

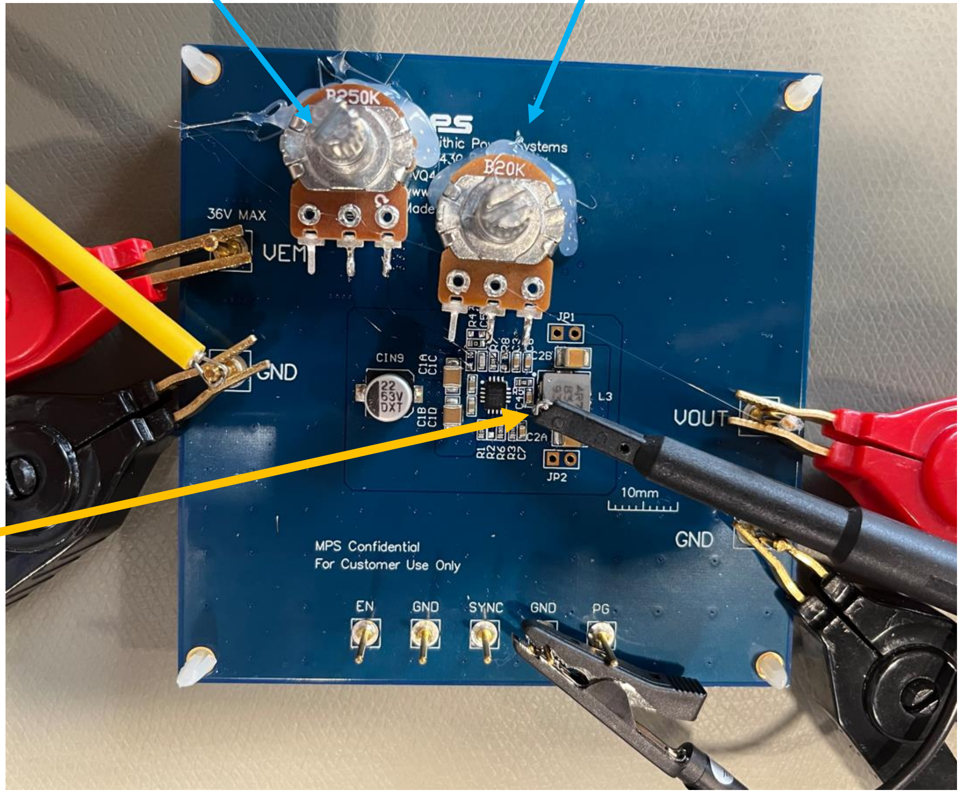
EVALUATION BOARD SCHEMATIC



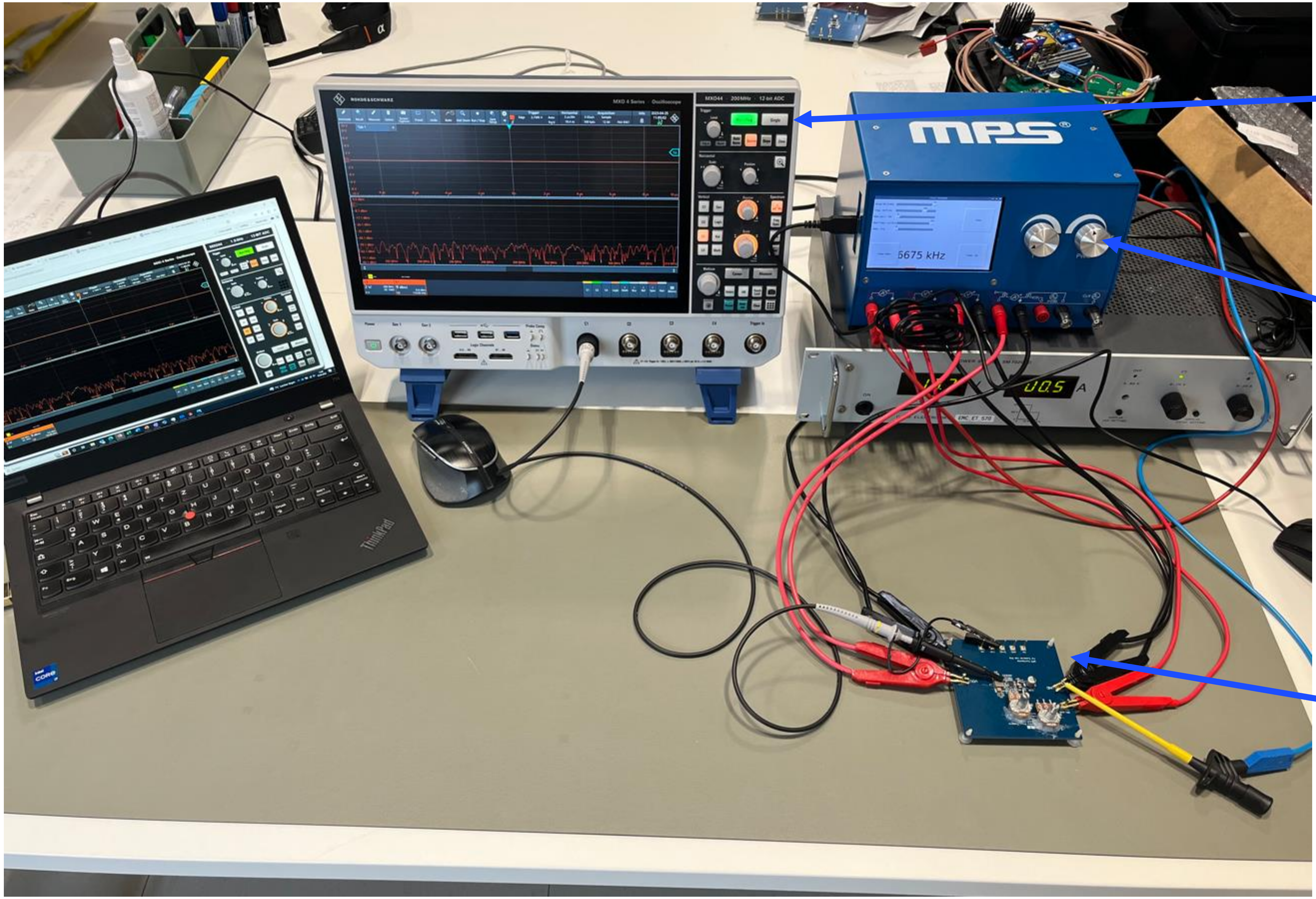
Direct connection of the Probe to the SW Node

Trim Frequency

Trim Duty Cycle



Spectrum of a Traditional SMPS



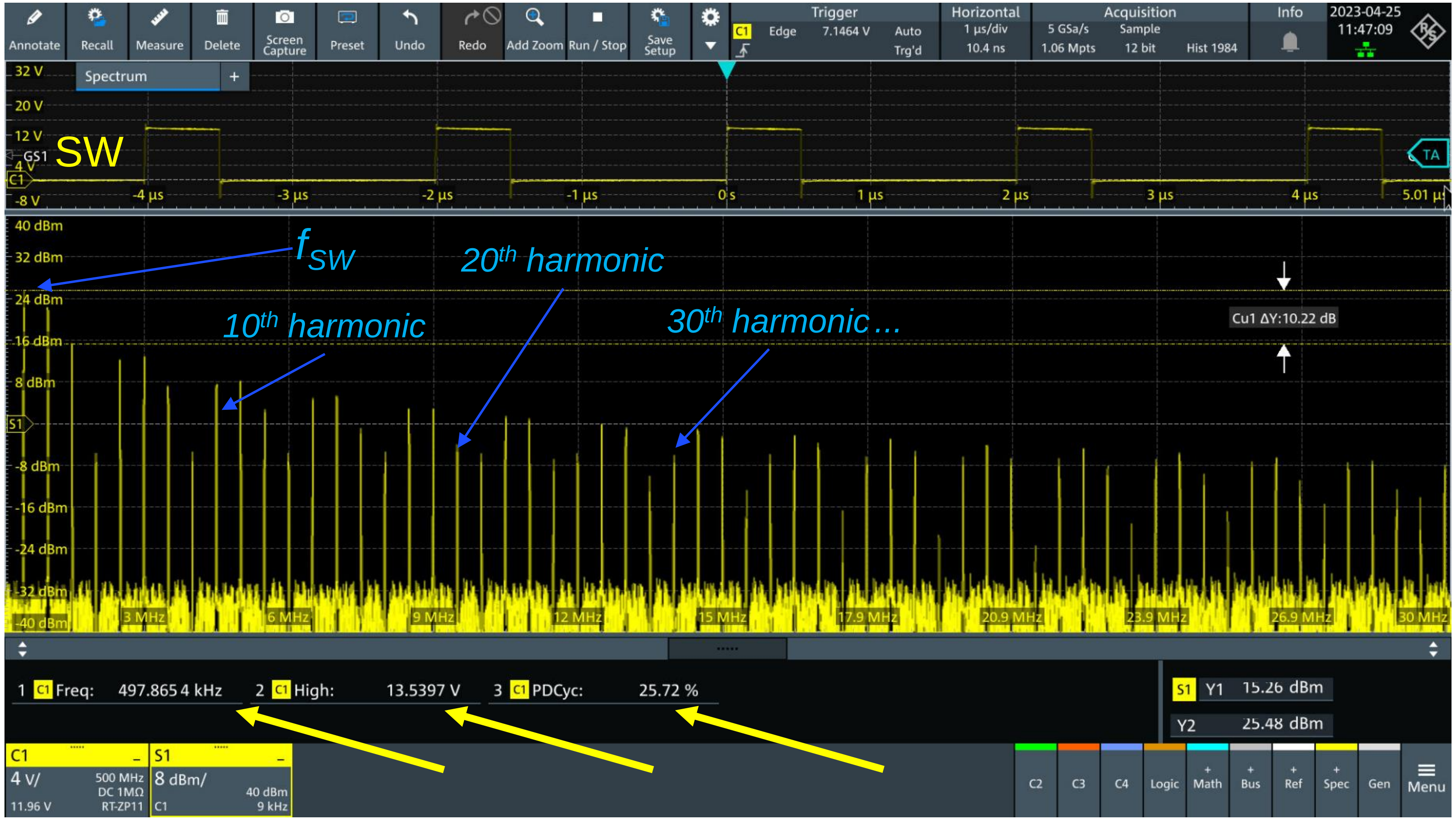
R&S MXO 4 Oscilloscope
with real time FFT

MPS Efficiency Meter
(Used as Load)

EVQ4430-L-00A
Evaluation Board

Spectrum of a Traditional SMPS

Generally, the spectrum of a switched-mode power supply (SMPS) shows the switching frequency (f_{SW}) and all harmonics.



V_{IN} = 13.5V

V_{OUT} = 5V

f_{SW} = 500kHz

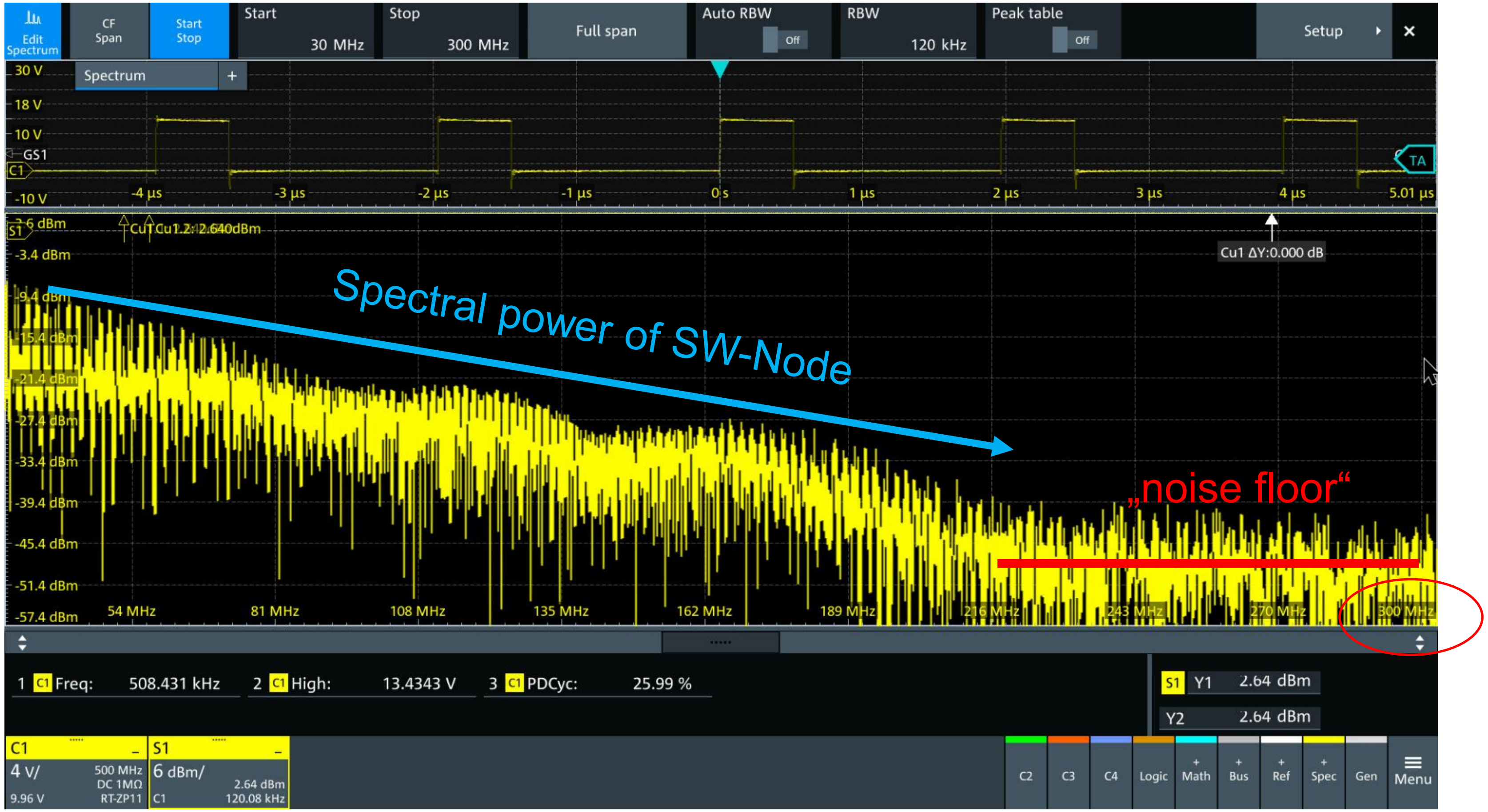
I_{OUT} = 1A

Mode = CCM

RBW = 9kHz

Spectrum of a Traditional SMPS

The power of the harmonics decreases with the frequency, and the noise level is about 300MHz to 700MHz depending on the switching frequency.



V_{IN} = 13.5V

V_{OUT} = 5V

f_{SW} = 500kHz

I_{OUT} = 1A

Mode = CCM

RBW = 9kHz

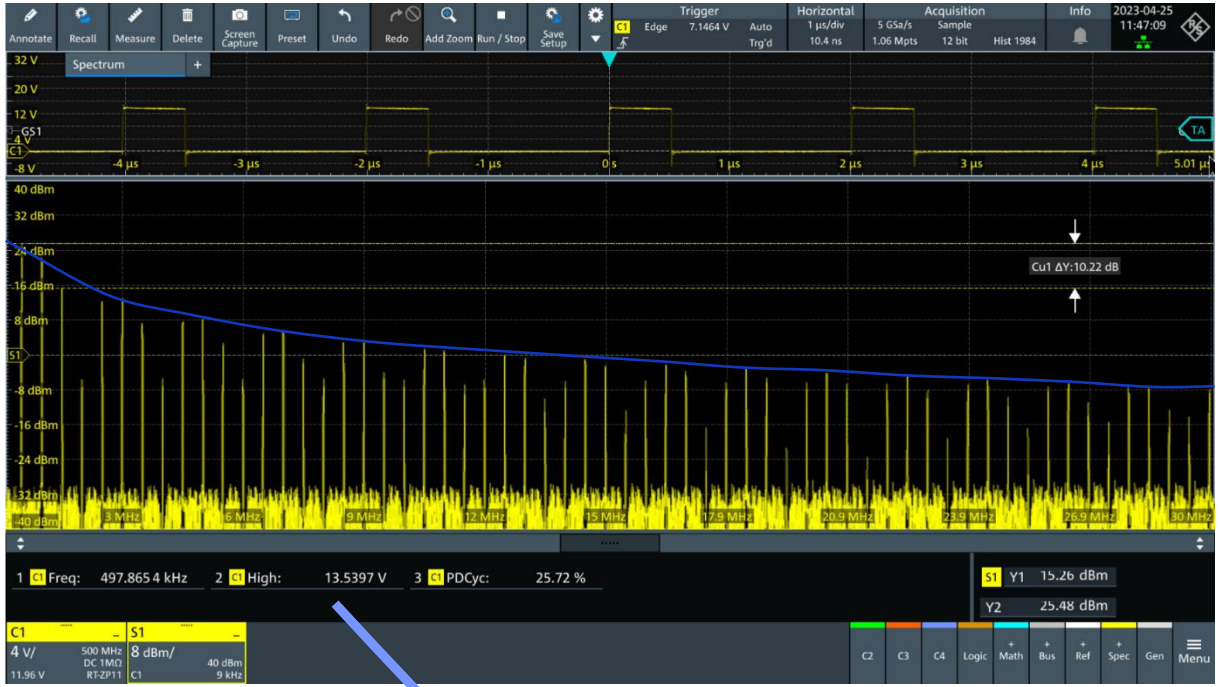
What Exactly Influences the Spectrum of an SMPS? And How?

Let’s explore the effect of the following parameters to the spectrum of an SMPS:

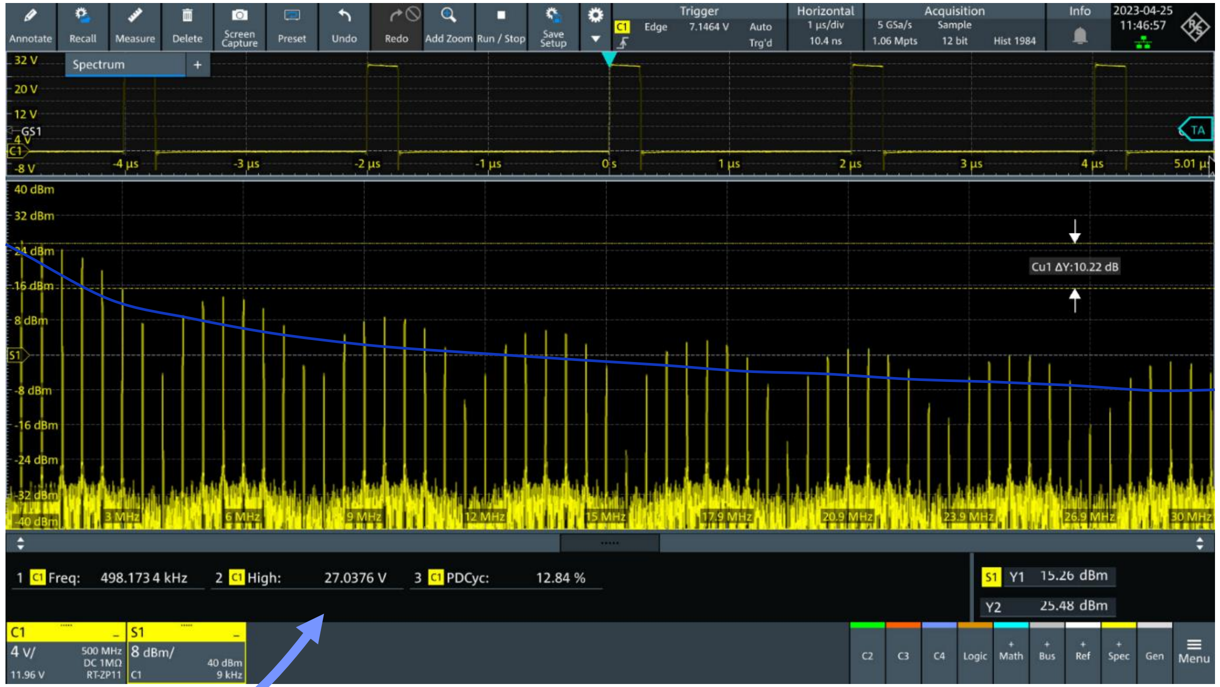
- Input voltage
- Duty cycle
- Switching frequency

Spectrum of a Traditional SMPS

Changing the input voltage from 13.5V to 27V:

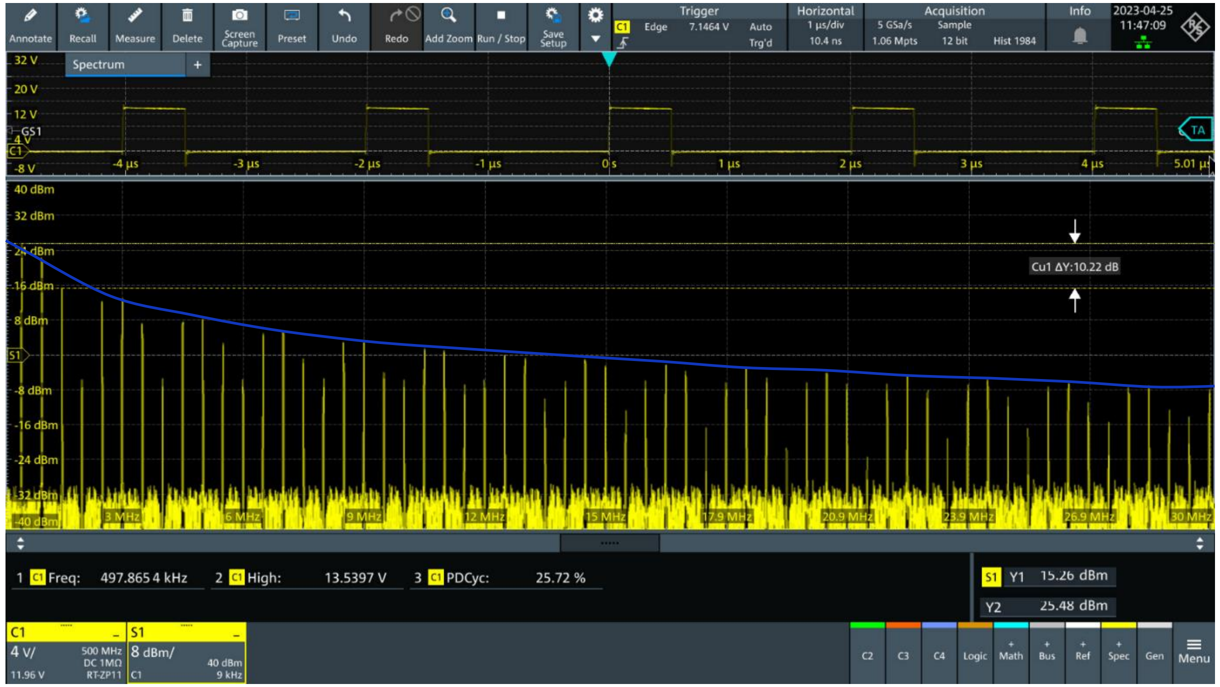


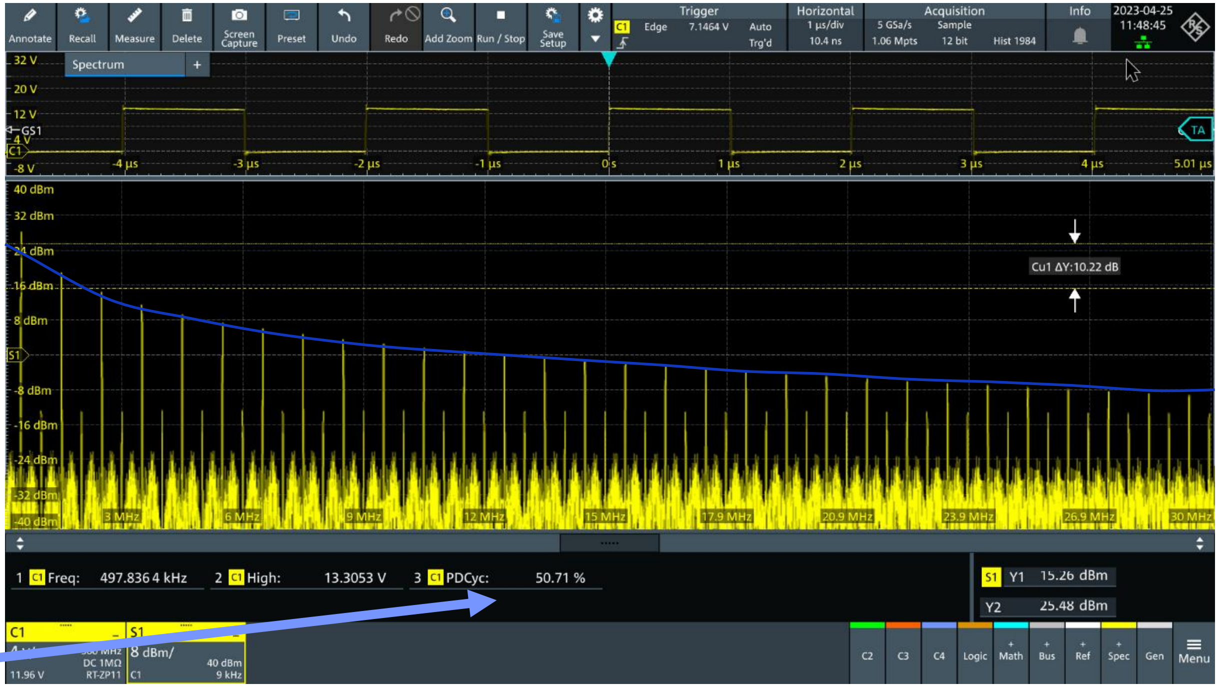
Higher Input voltage at a Buck regulator will lead to more EMC emissions, as the dU/dt on the „hot loop“ will be increased



Spectrum of a Traditional SMPS

Changing the duty cycle (means changing the DC output voltage):

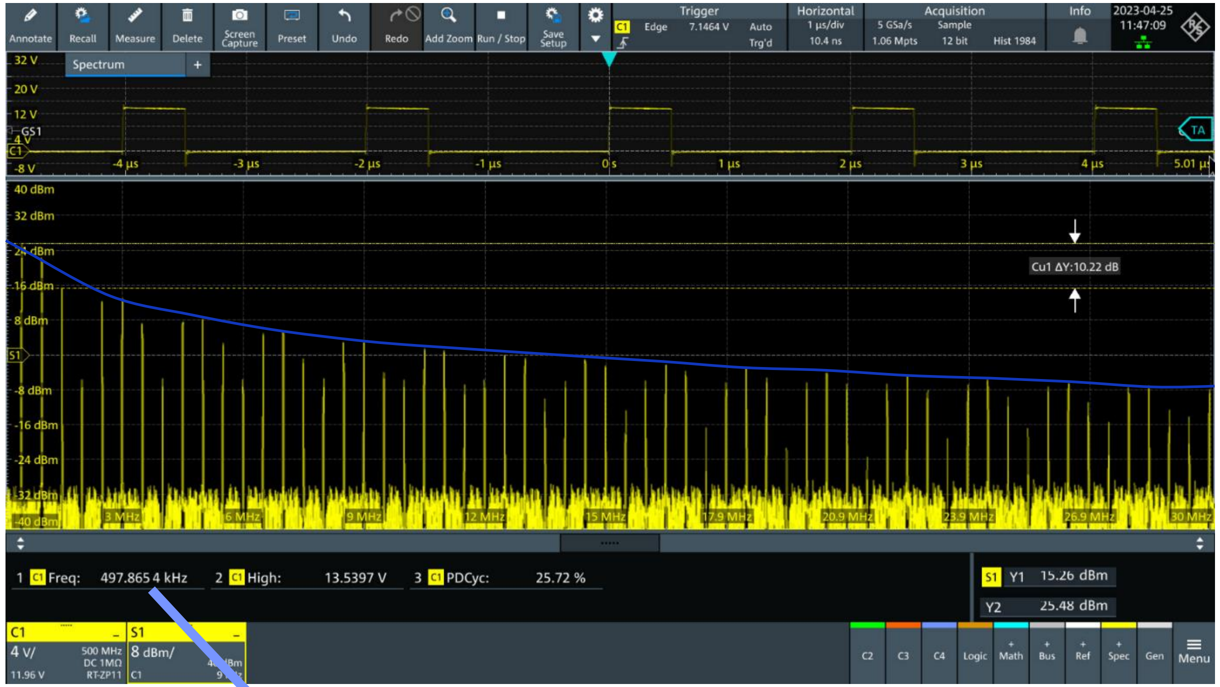




At exactly 50% Duty-Cycle, all „Even“ Harmonics will disappear

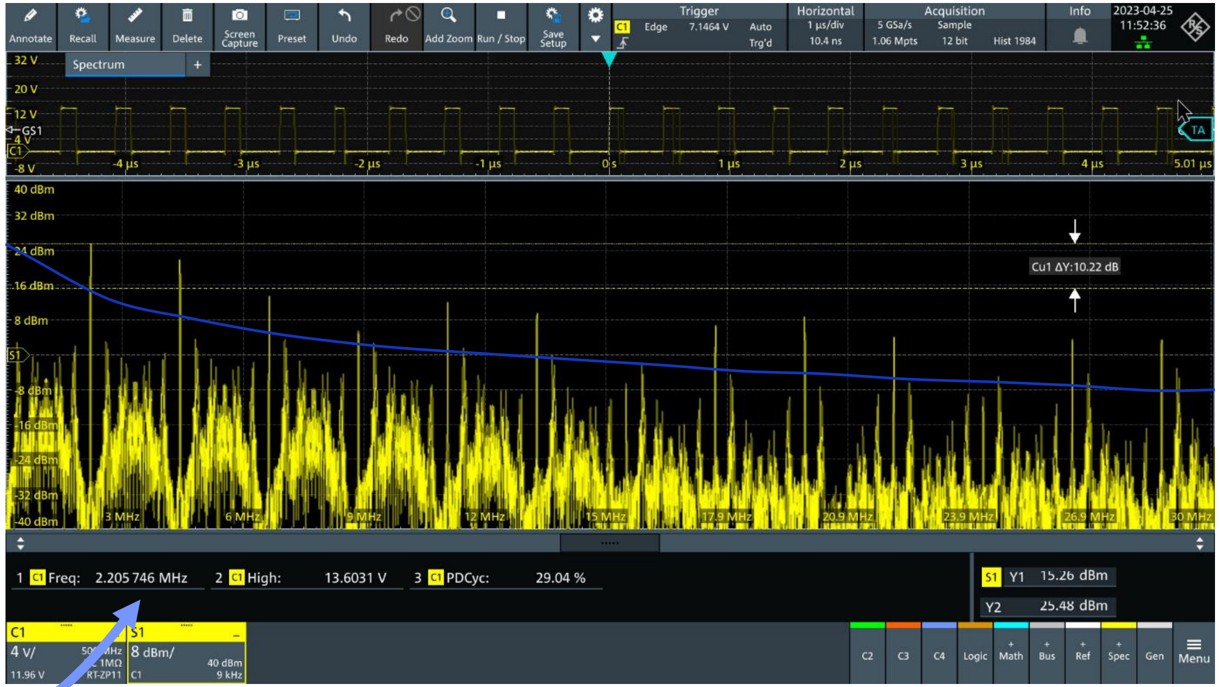
Spectrum of a Traditional SMPS

Changing the frequency LF:



Increasing the switching frequency will increase the EMC Emissions for each specific frequency, where the harmonic will stand.

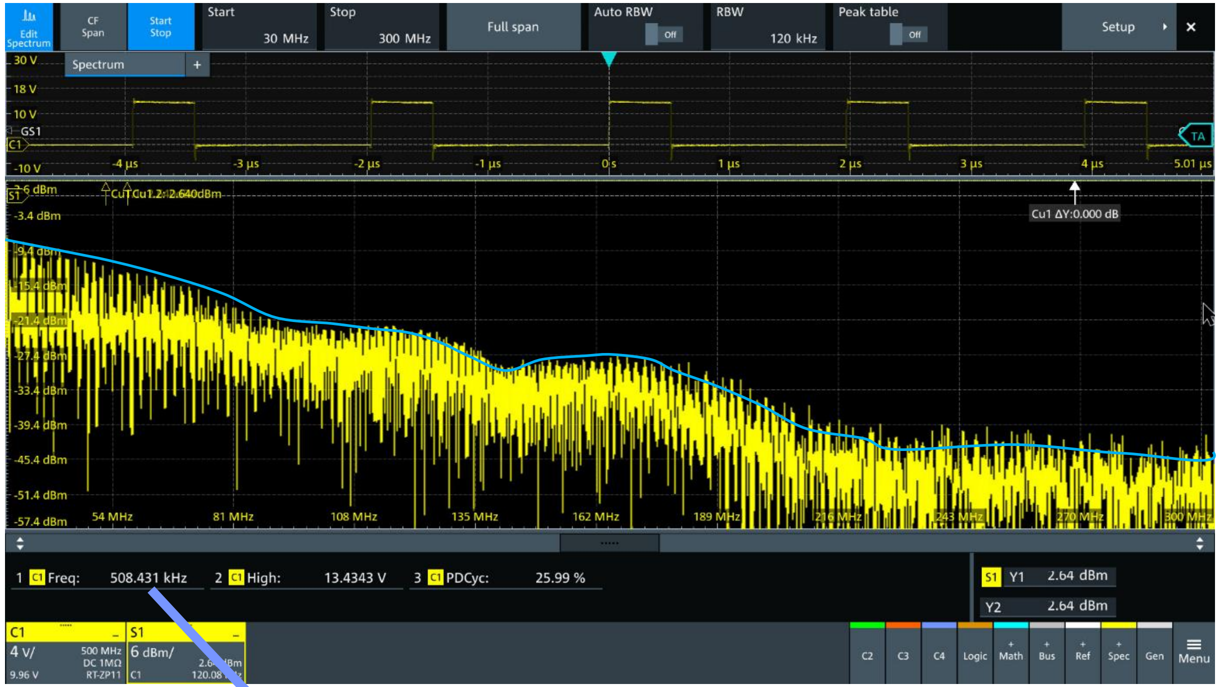
In the same way, the „gaps“ between the harmonics are also bigger

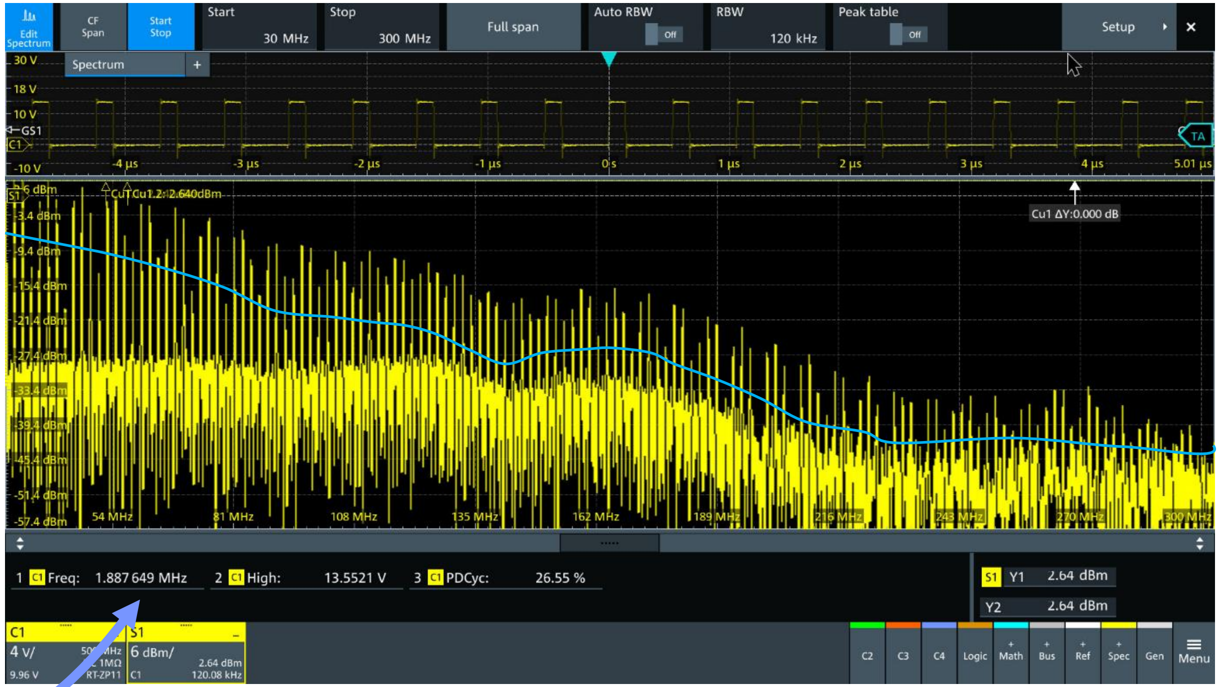


Spectrum of a Traditional SMPS

Changing the frequency HF:

Double the switching frequency leads to a increase of the EMC Emissions of 6dB





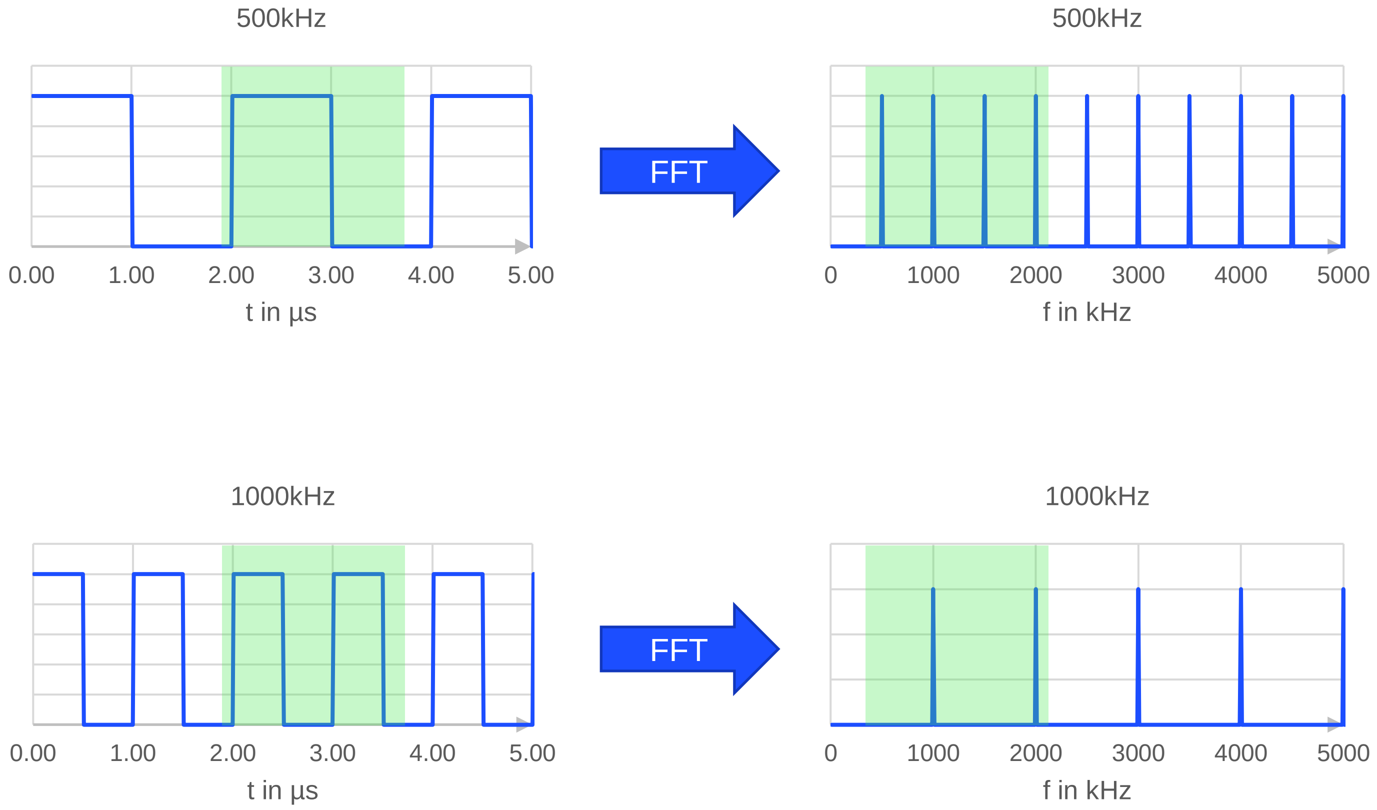
Spectrum of a Traditional SMPS

Increasing the frequency means

- **Twice as many switching flanks per time frame**

  and

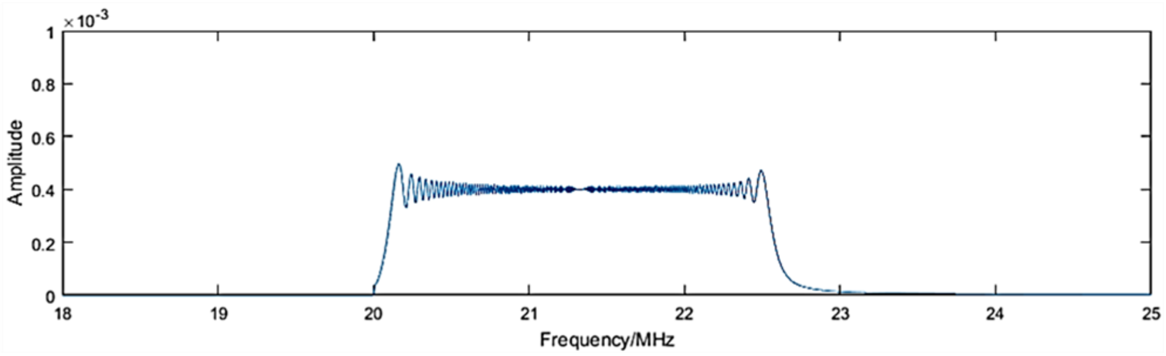
- **Half as many spikes where the energy can be transformed to**



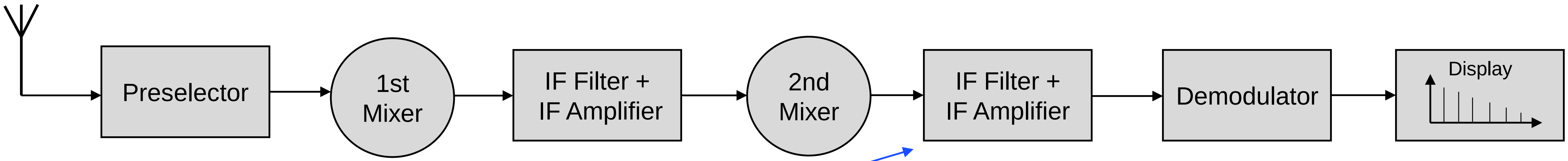
This increased the "spikes" in the spectrum by

$$\frac{6dB}{frequency\ doubling}$$

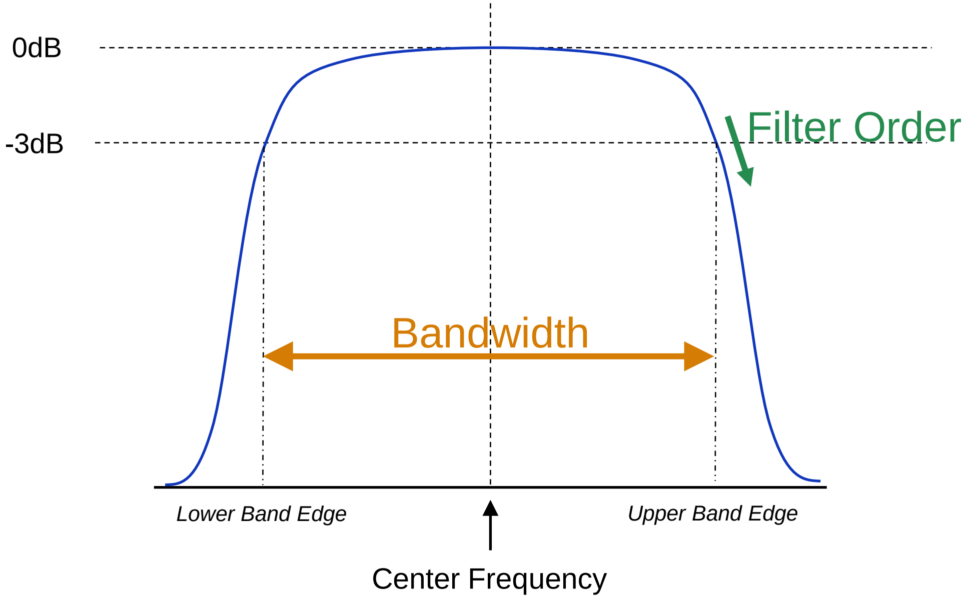
Theory behind Frequency Spread Spectrum (FSS)



EMI Receiver Block Diagram



Resolution Bandwidth (RBW) Filter



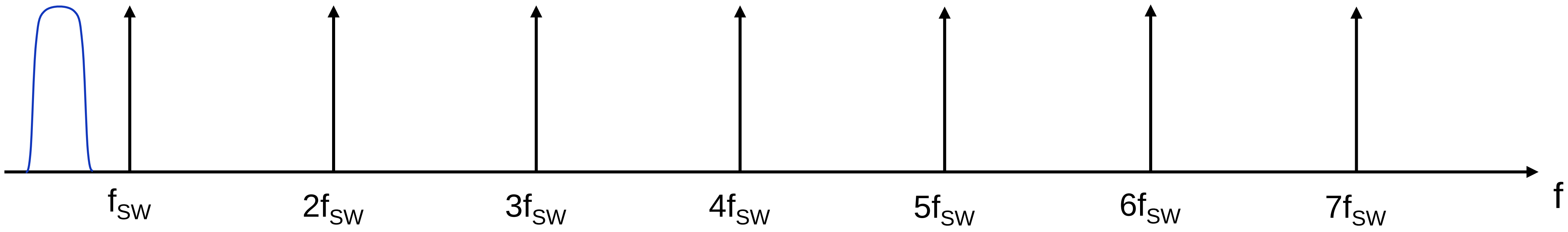
Because the RBW filter is before the demodulator in this process, and therefore the part creating power out of the signal, this is the spot where frequency spread spectrum (FSS) has the most impact on the EMI receiver

EMI Receiver Spectrum Measurement

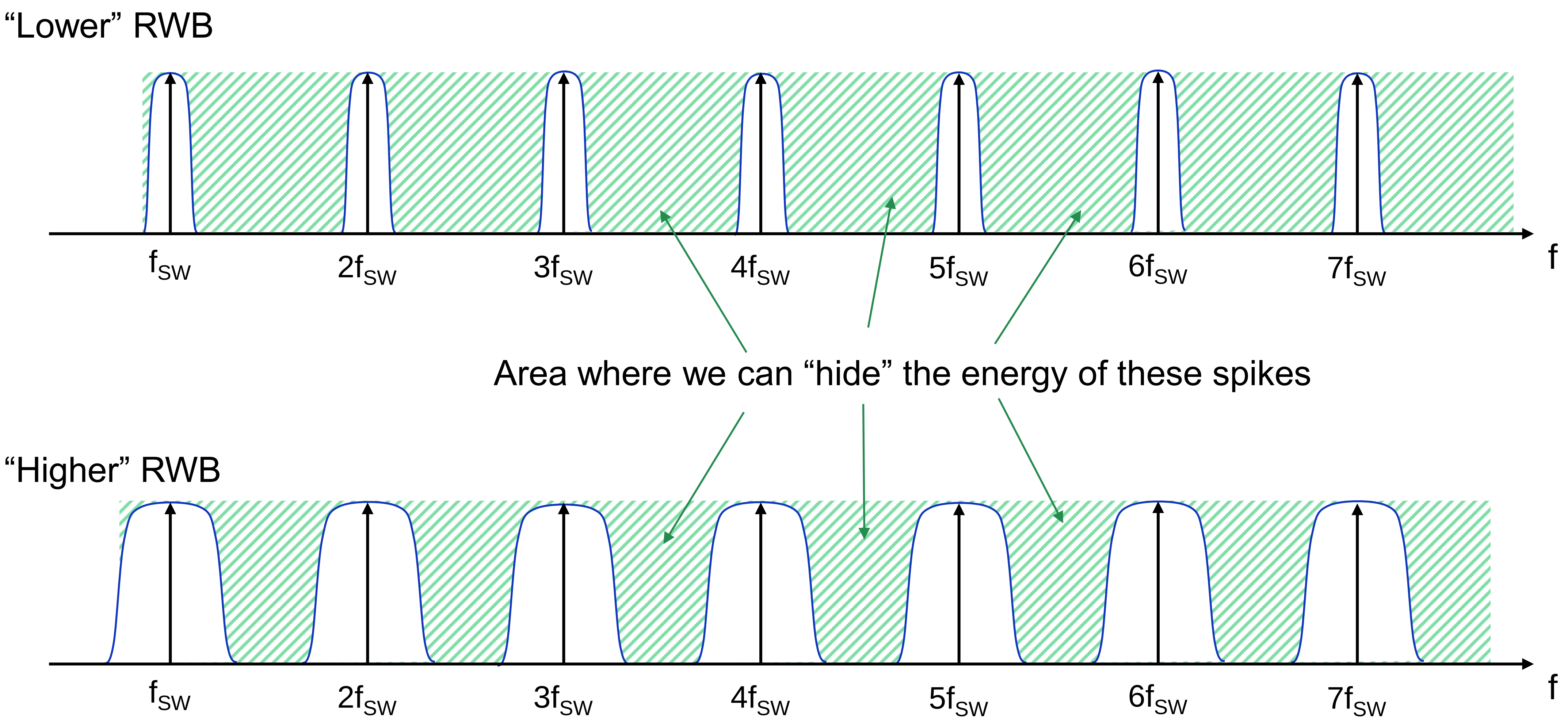
The RBW moves with constant frequency change through the selected frequency span from the starting frequency to the stopping frequency.

Typically there are three RBWs:

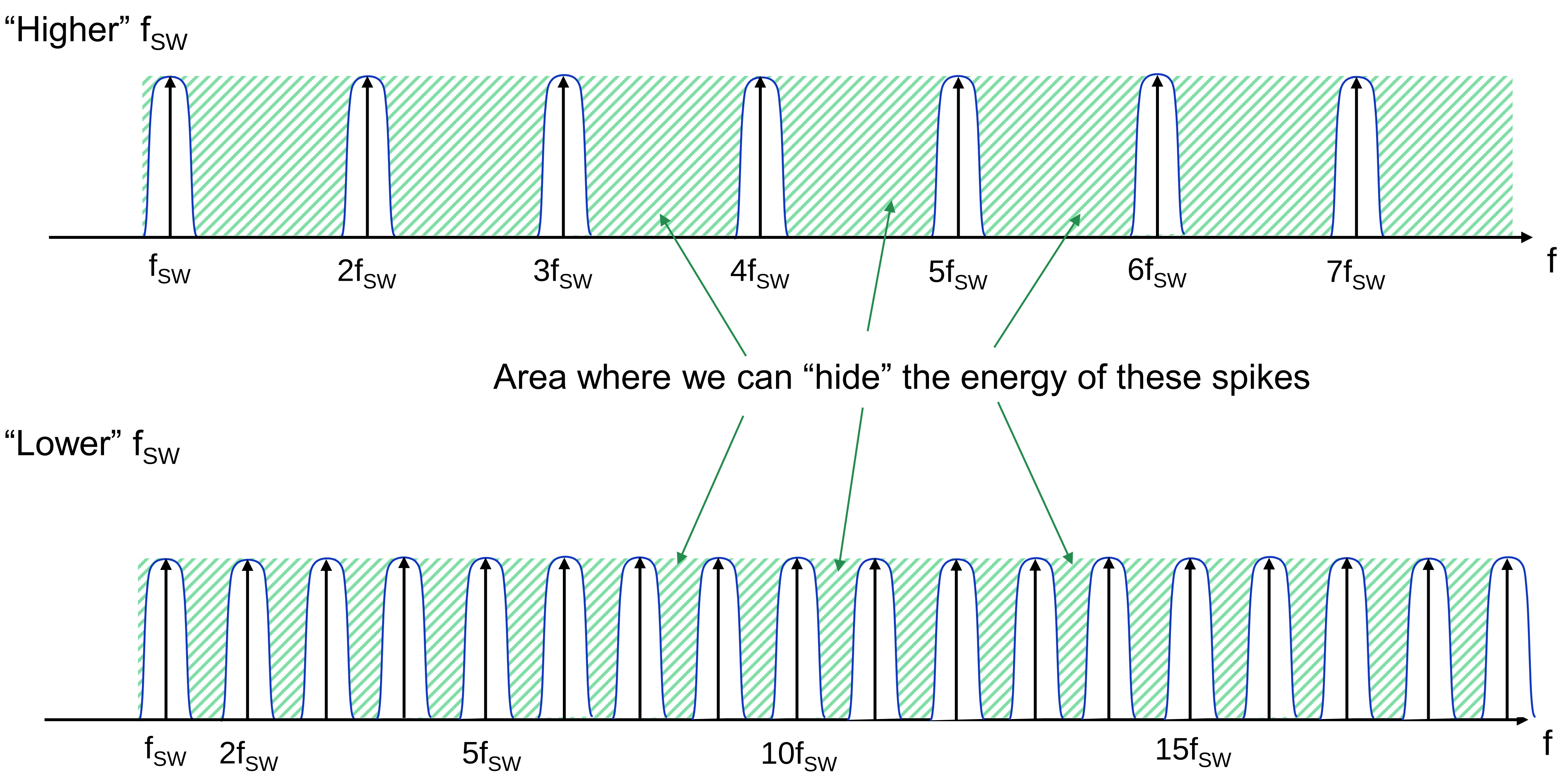
- 9kHz (Mostly used in lower frequency ranges, up to 30MHz)
- 120kHz (Mostly used in mid-frequency ranges, between 30MHz and 1GHz)
- 1MHz (Mostly used in high-frequency ranges, >1GHz)



Potential to Hide Energy of the Spikes



Potential to Hide Energy of the Spikes

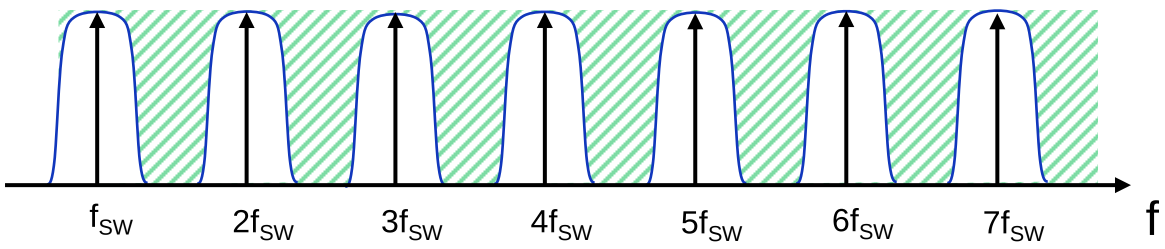


Potential to Hide Energy of the Spikes

The energy that can be "hidden" from the EMI receiver is not unlimited. The higher the RBW become, the lower the effect of using FSS. In addition, the lower f_{SW}, the lower the effect of FSS, as the spikes collapse in the frequency band.

The maximum attenuation (if using the entire green area to "hide" the energy from the spikes, resulting in white noise) can be calculated with the equation below:

$$\alpha = 10 * \log\left(\frac{RBW}{f_{SW}}\right)$$

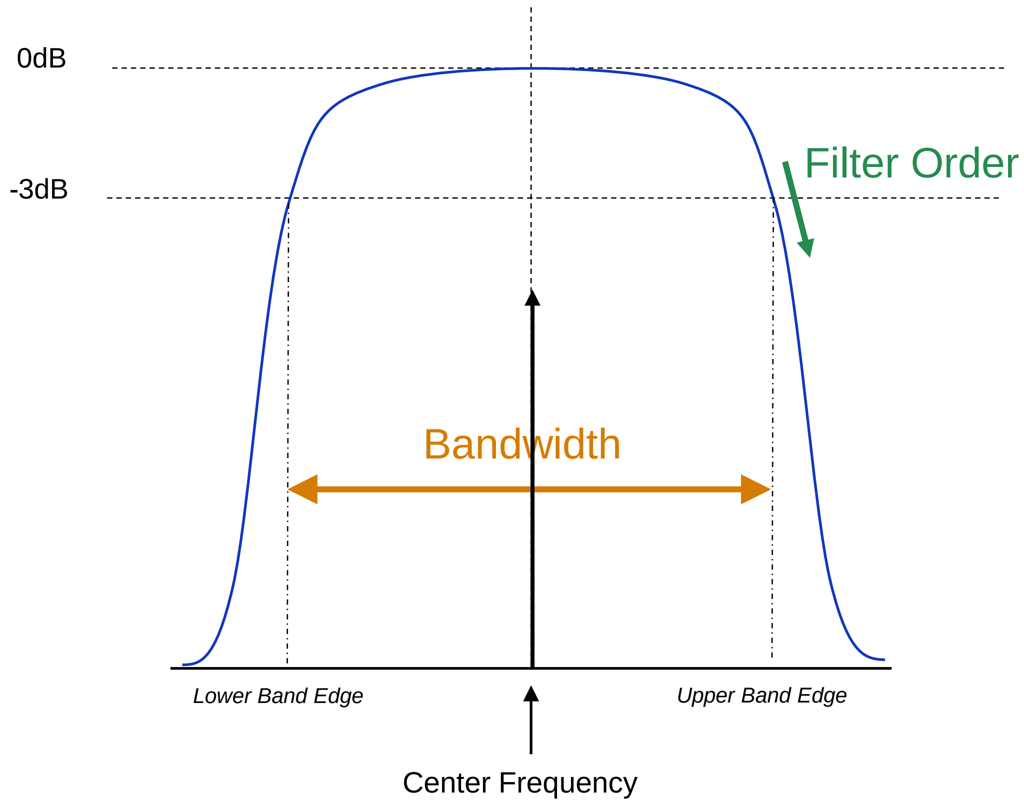


f_{SW} (MHz)	Attenuation for RBW (dB)		
	9kHz	120kHz	1000kHz
0.1	10.5	0.0	0.0
0.2	13.5	2.2	0.0
0.3	15.2	4.0	0.0
0.5	17.4	6.2	0.0
1	20.5	9.2	0.0
2	23.5	12.2	3.0
5	27.4	16.2	7.0
10	30.5	19.2	10.0
100	40.5	29.2	20.0

Convert the Spikes into FSS

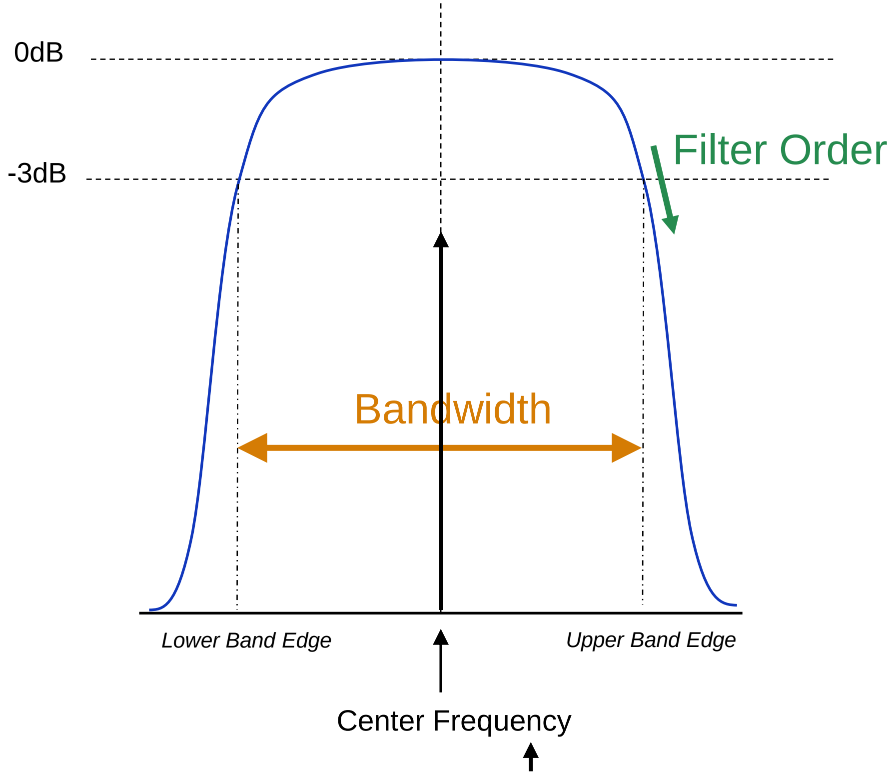
To convert the spikes from a switched node in the spectrum to white noise (or at least into an FSS signal), the frequency mustdither around its original frequency.

But how does one dither around the original frequency?



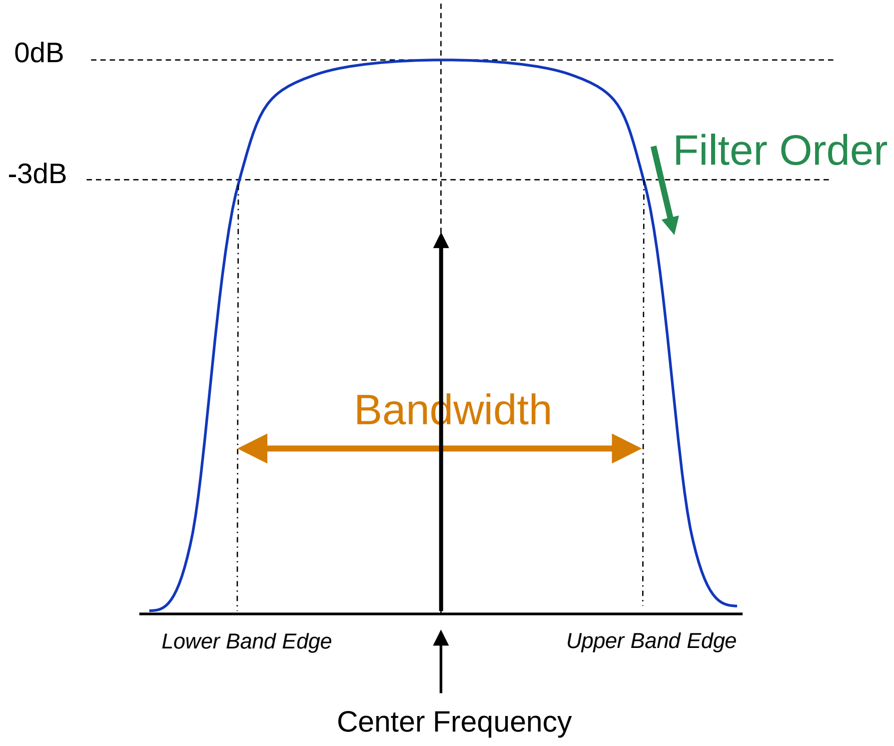
Limitations of FSS

Case 1:
FSS is too "slow"



If the carrier frequency stays "too long" inside the bandwidth of the RBW filter, there will be **no attenuation.**

Case 2:
Amplitude is too small



If the carrier frequency change is too small to reach the lower or upper band edge, the **attenuation** of the original carrier will be **0!**

Convert the Spikes into FSS

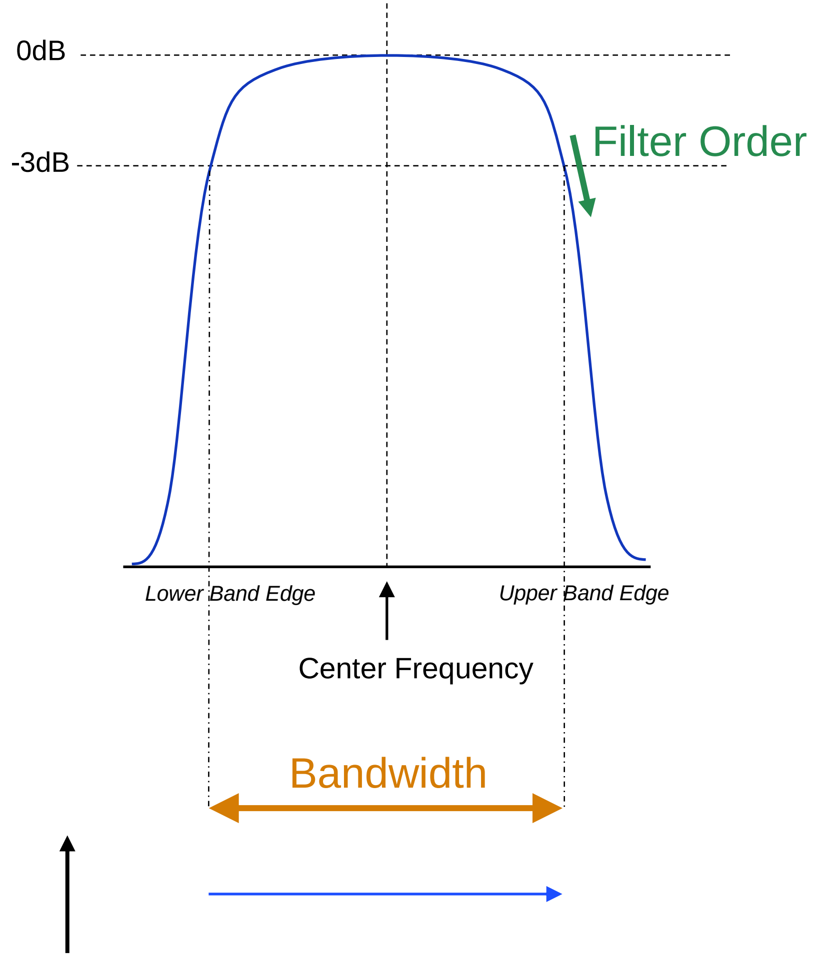
To reach a certain attenuation, the frequency must pass the bandwidth faster than the settling time of the bandpass filter.

This settling time can be calculated with $\frac{1}{RBW}$

$$RBW = 9kHz \rightarrow Settling\ time = \frac{1}{9kHz} = 111\mu s$$

$$RBW = 120kHz \rightarrow Settling\ time = \frac{1}{120kHz} = 8.33\mu s$$

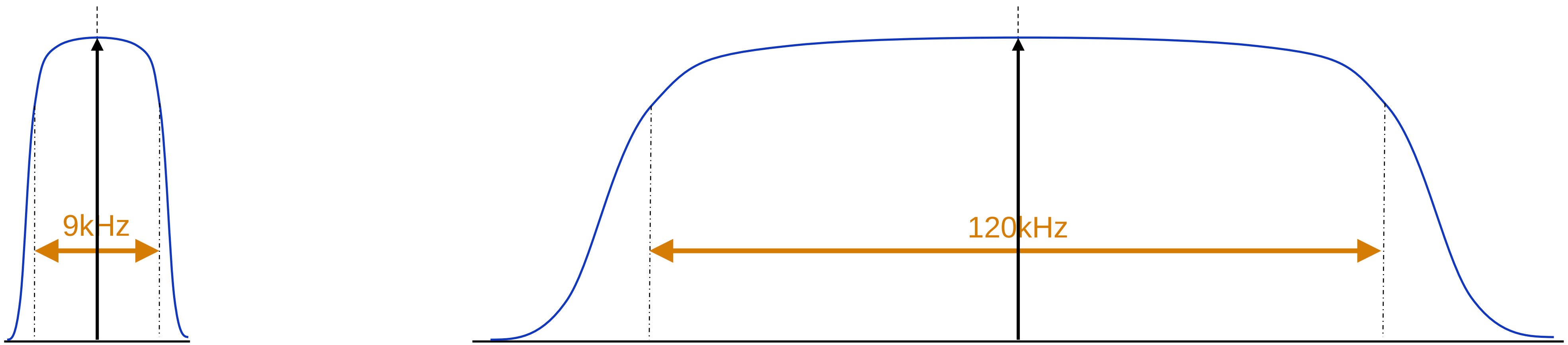
$$RBW = 1000kHz \rightarrow Settling\ time = \frac{1}{1000kHz} = 1\mu s$$



Convert the Spikes into FSS

As the settling time decreases with the bandwidth, the speed of the frequency change must be in square to the RBW:

$$Frequency\ change\left[\frac{Hz}{s}\right] = \frac{RBW}{Settling\ time} = \frac{RBW}{\frac{1}{RBW}} = RBW^2$$



This leads to the fact that the frequency change must be faster than:

- 9kHz RBW → Settling Time = 111µs → 81MHz/s
- 120kHz RBW → Sellting Time = 8.33µs → 14.4GHz/s
- 1000kHz RBW → Settling Time = 1µs → 1THz/s

Convert the Spikes into FSS

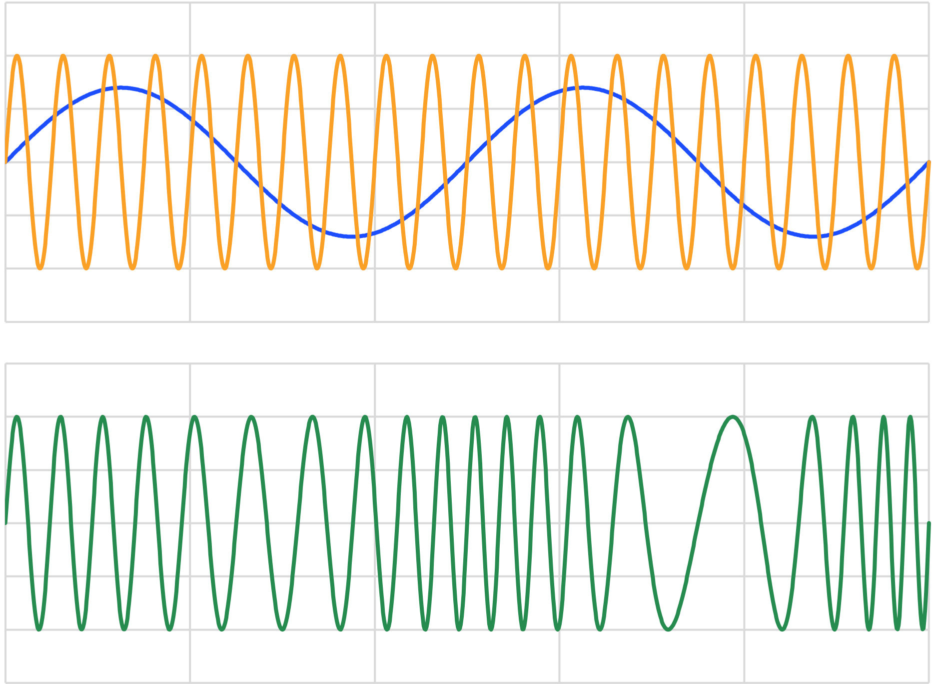
When moving around the original f_{SW} of an SMPS, the method to modulate a spread spectrum signal is called frequency modulation (FM).

Frequency Modulation: FM

Modulation Depth: $\Delta f = f_{Max} - f_{Min}$

Modulation Index*: $h = \frac{\Delta f}{FM}$

$$h = \frac{Spread\ of\ the\ Frequency}{\frac{1}{Number\ of\ points, how\ often\ we\ go\ through\ the\ Spread\ of\ the\ Frequency\ per\ second}}$$



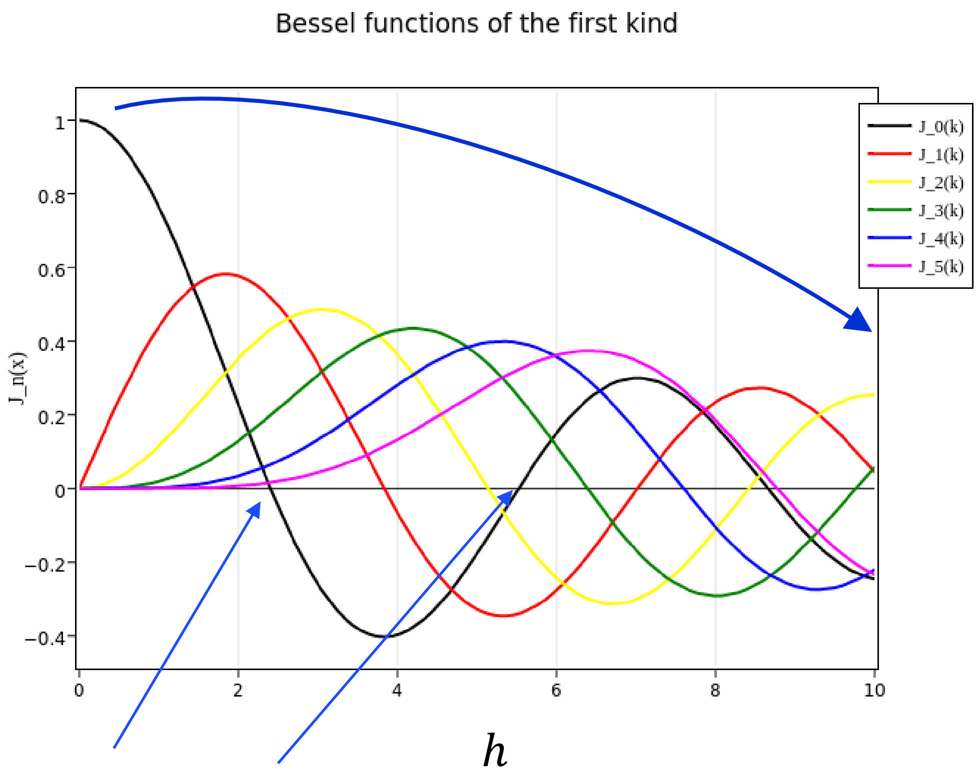
** The modulation index indicates how much the modulated signal varies around its unmodulated signal*

Convert the Spikes into FSS

According to the Bessel functions of the first kind, the modulation index indicates how much of the carrier frequency power is transferred to the sidebands.

In general, high modulation frequencies lead to a smaller carrier frequency amplitude.

There are some modulation index points at which the carrier frequency becomes 0.



$$h = \frac{\Delta f}{FM}$$

Increase the frequency span
We can't go to infinity (SMPS regulation loop)!

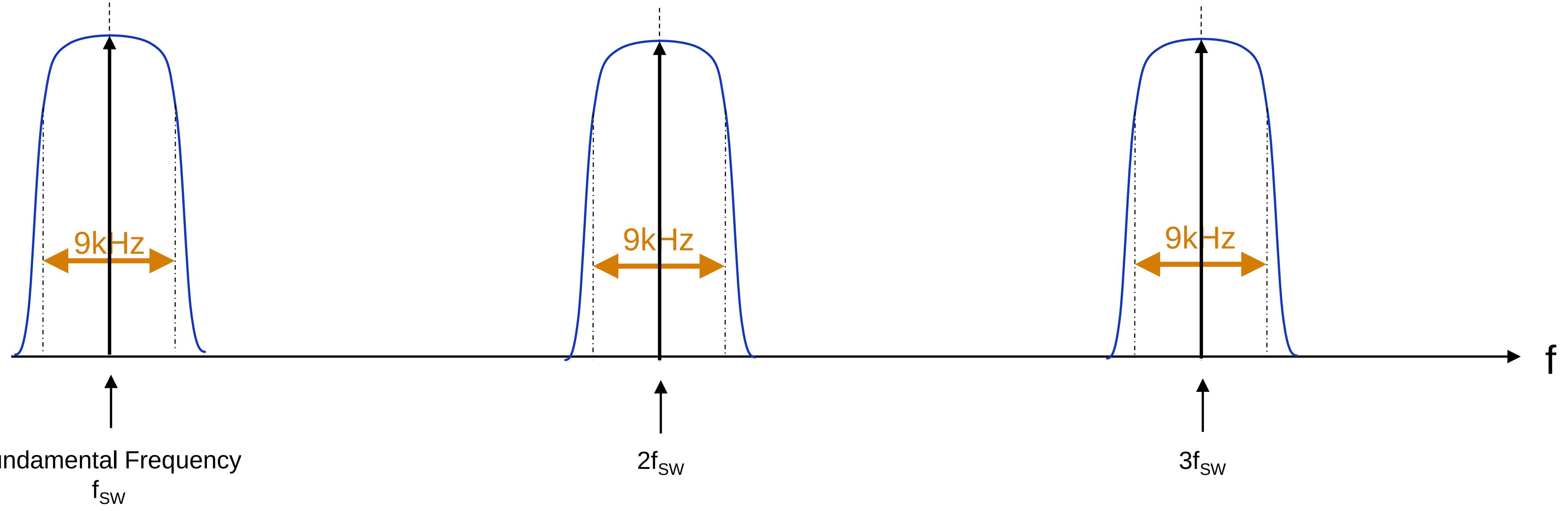
Decrease the FM
If this becomes too low, it violates the settling time criteria and the attenuation becomes 0!

MPS

Convert the Spikes into FSS

i.e. Frequency Modulation = 10kHz
Modulation Depth = 10kHz
FM Modulation on the Fundamental Frequency

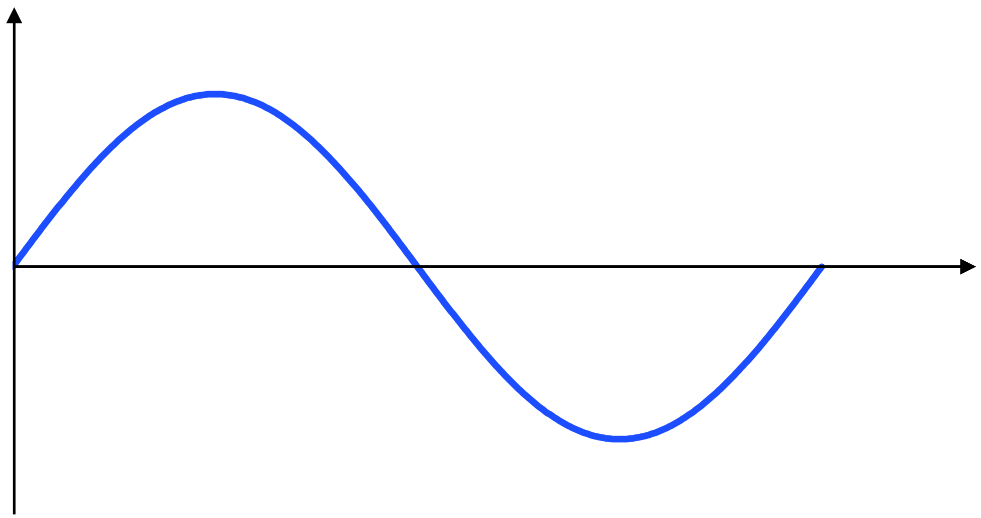
$$h = \frac{10kHz}{10kHz} = 1 \qquad h = \frac{20kHz}{10kHz} = 2 \qquad h = \frac{30kHz}{10kHz} = 3$$



High harmonics will automatically achive a high modulation index

Waveform of the FM?

To achieve a good attenuation, it is important to have a constant frequency change as well as a repetitive signal.

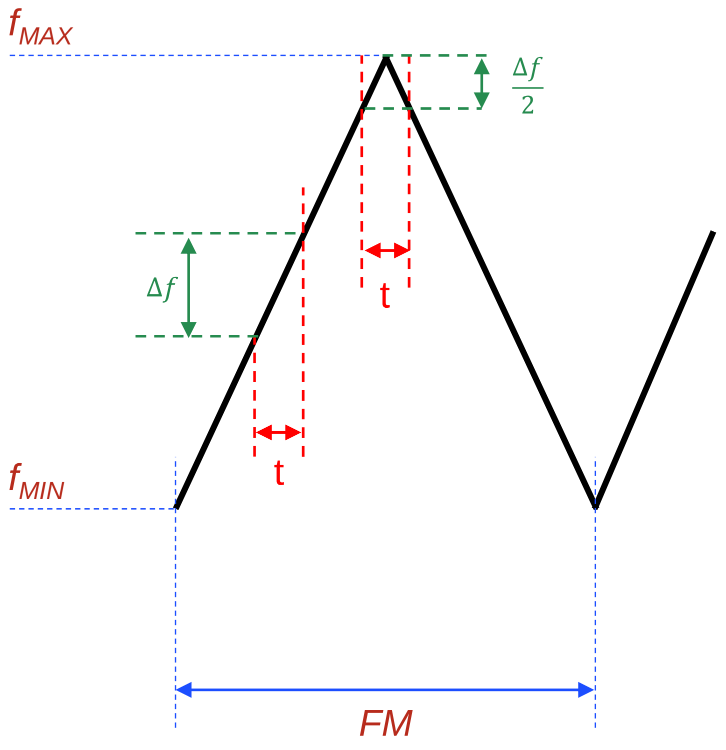


Modulation Waveforms

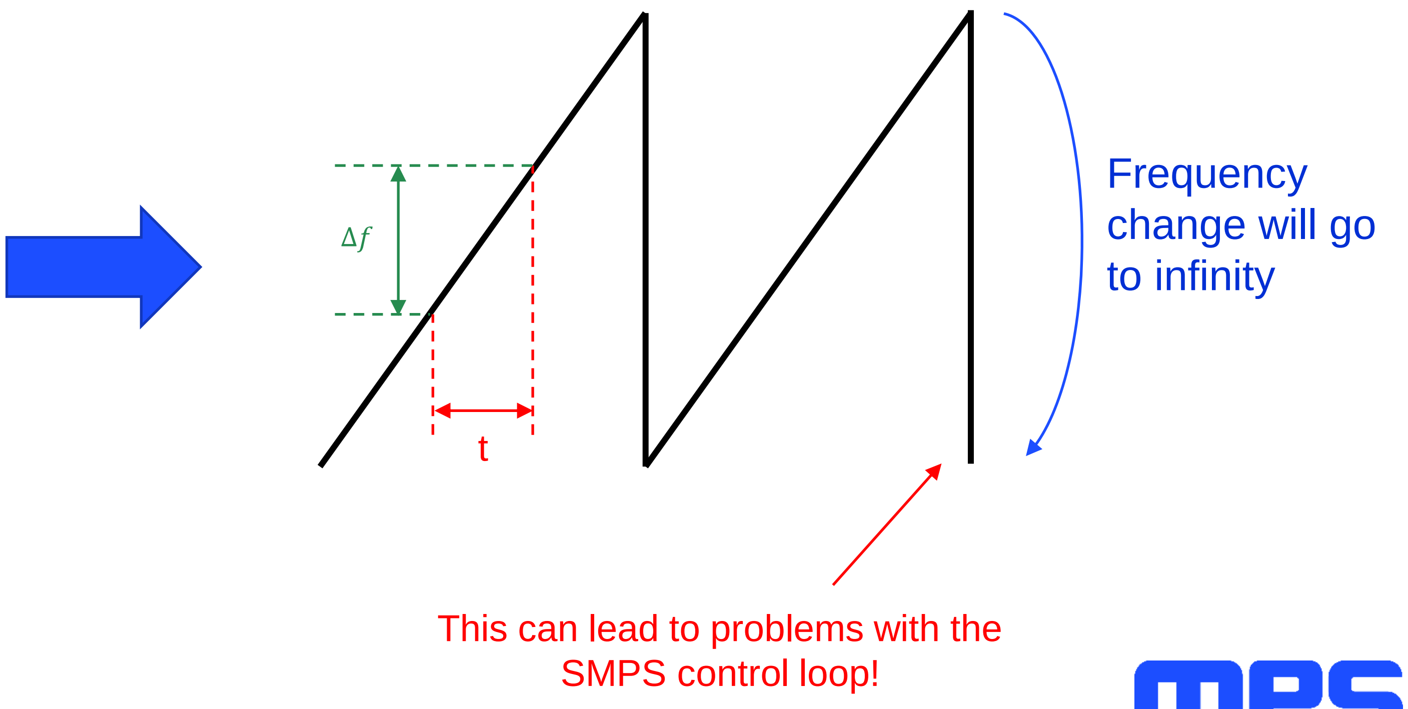
To achieve a good attenuation, it is important to have a constant frequency change, as well as a repetitive signal.

Therefore, different waveforms can be used for FM:

Triangular



Sawtooth

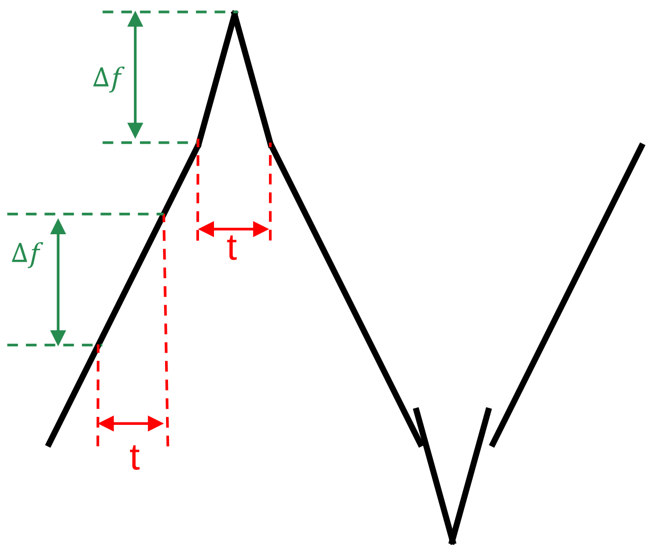


Modulation Waveforms

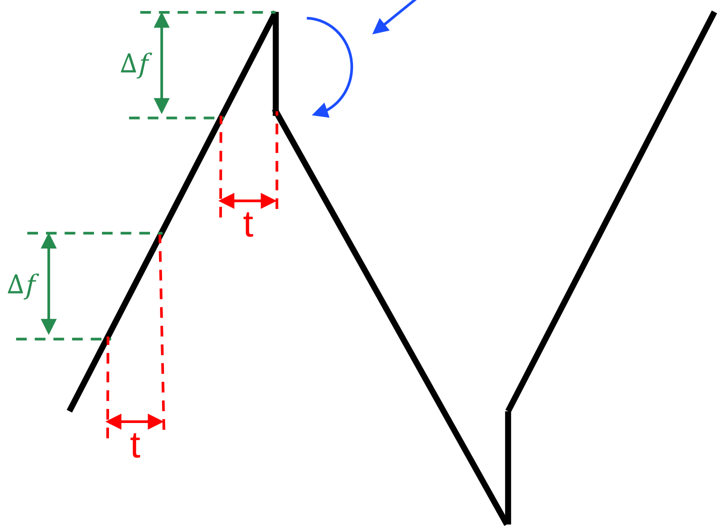
To achieve a good attenuation, it is important to have a constant frequency change, as well as a repetitive signal.

Therefore, different waveforms can be used for FM:

Hershey Kiss



Stepped Triangular

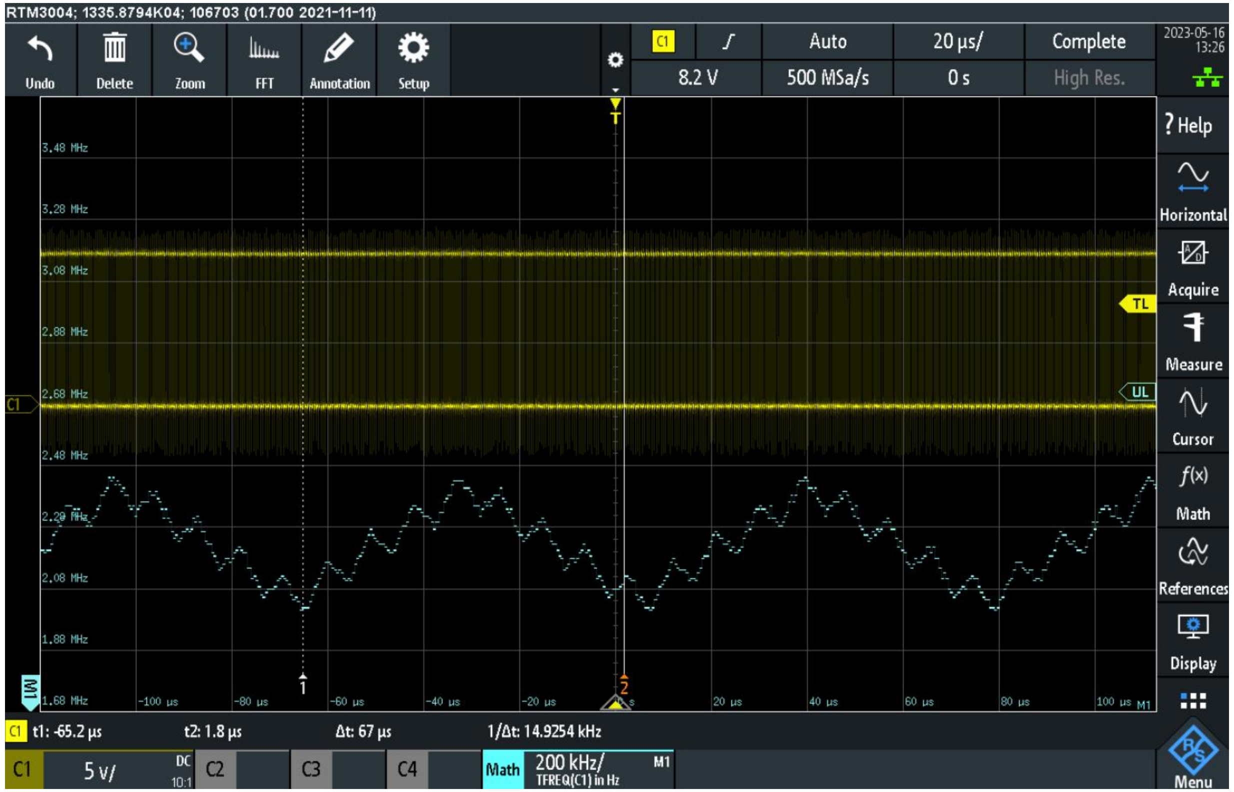


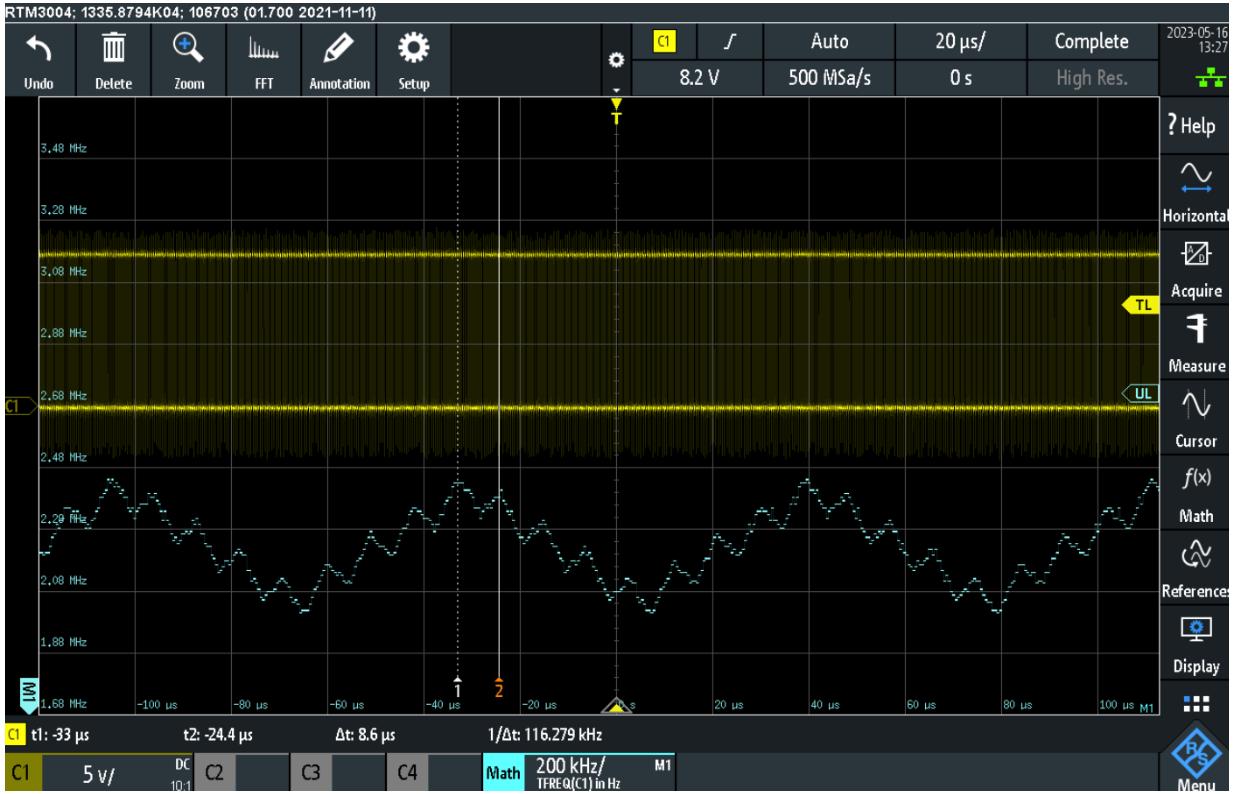
A smaller frequency change can help keep the control loop stable

Modulation Waveforms

To achieve a good attenuation, it is important to have a constant frequency change, as well as a repetitive signal. Therefore, different waveforms can be used for FM:

15kHz and 120kHz Modulation



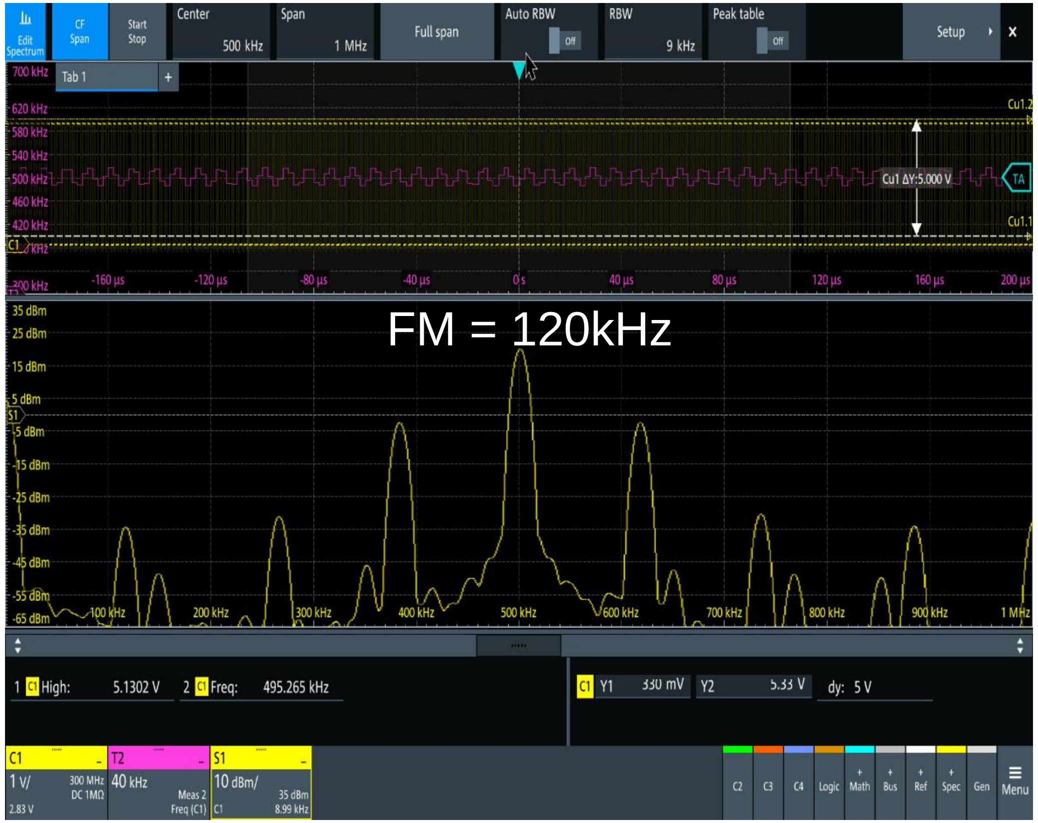


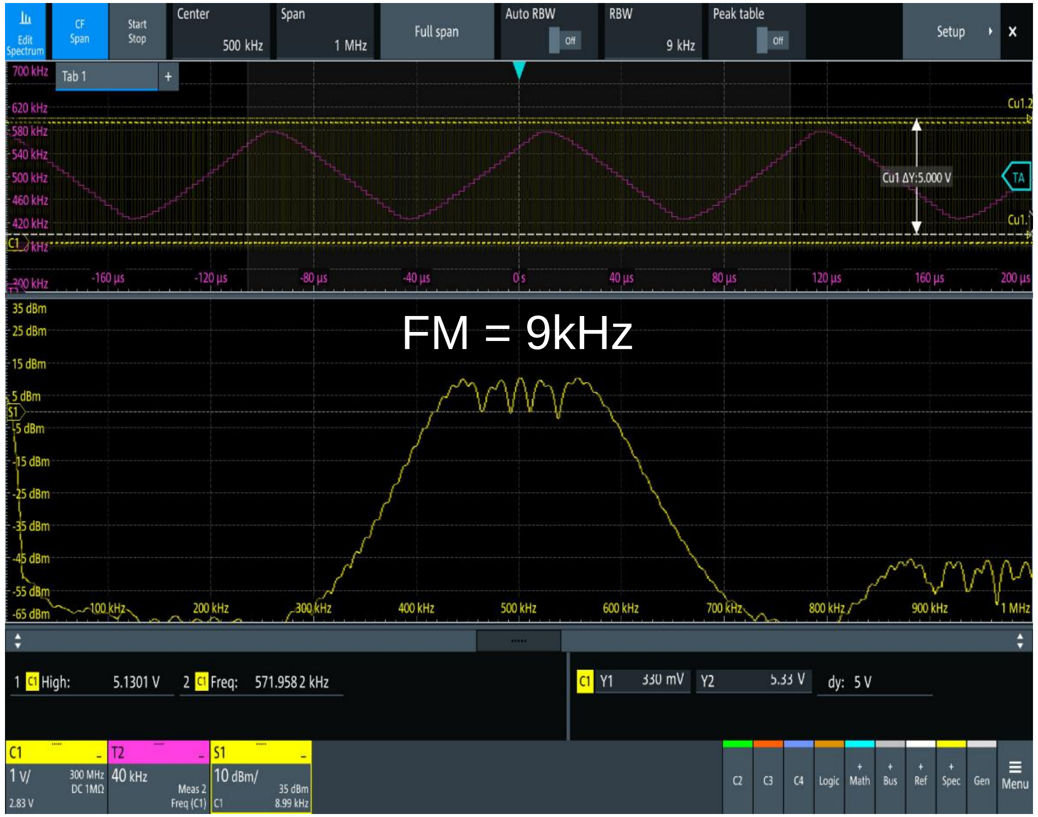
Measured with MPQ4371GVE-0000-AEC1 and 011 Frequency Spread Spectrum

Benefits of Practical Measurements on Real Boards

Measurements

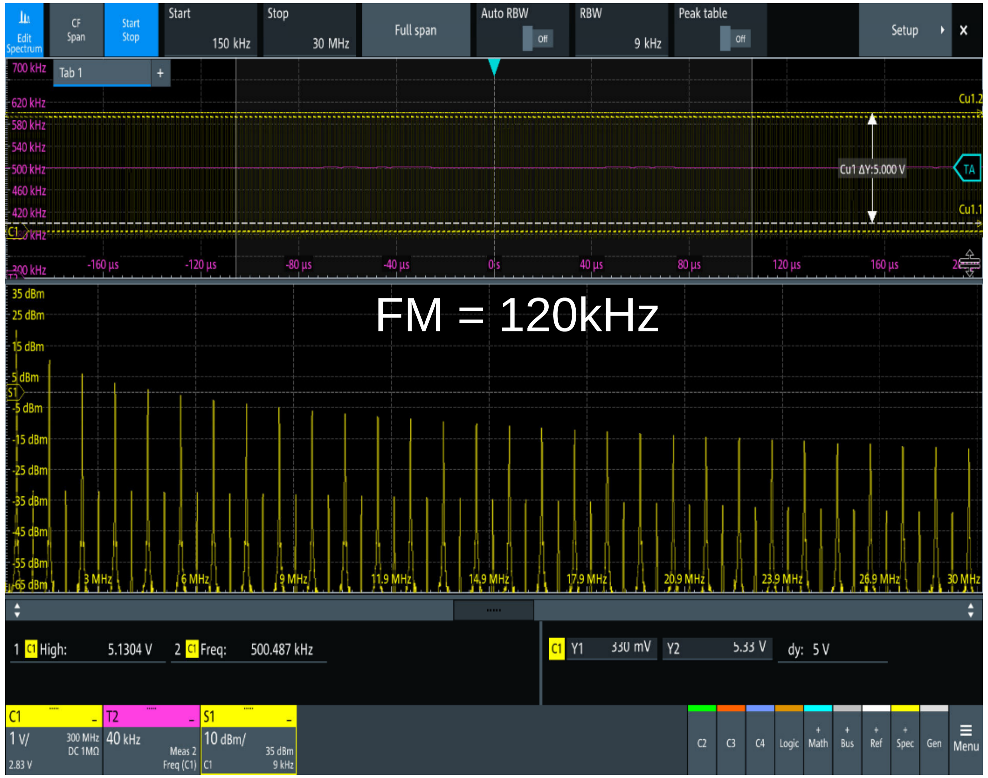
Carrier Frequency = 500kHz
Δf = 20% → 100kHz
FM → Sweep from 120kHz to 2kHz

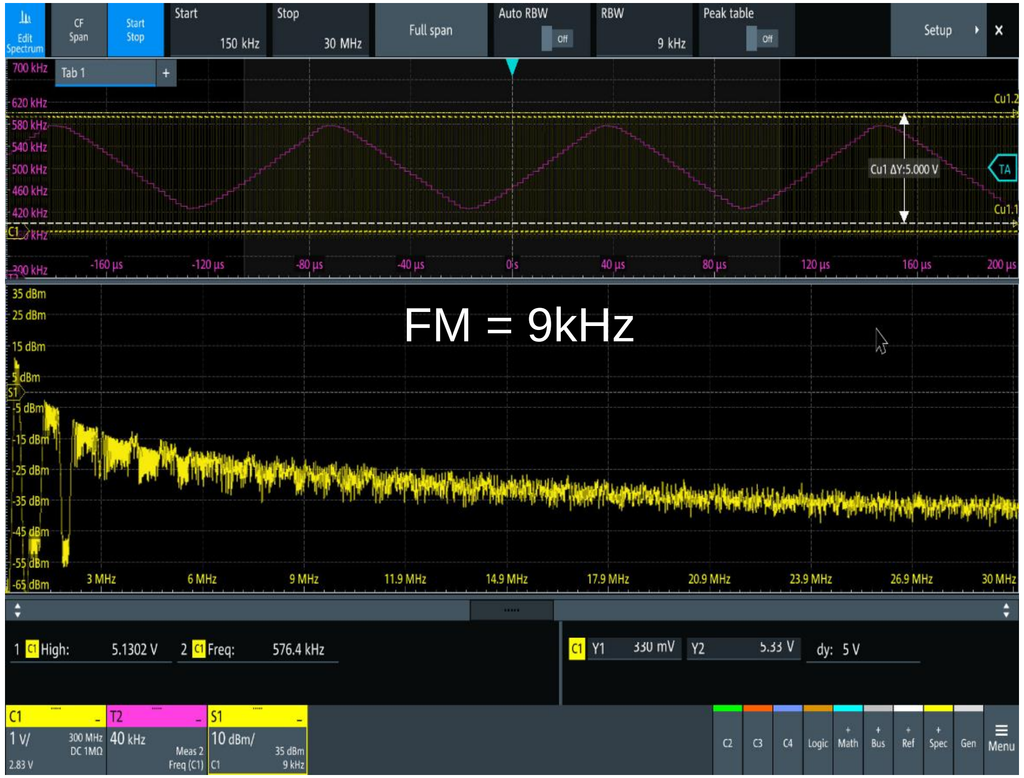




Measurements

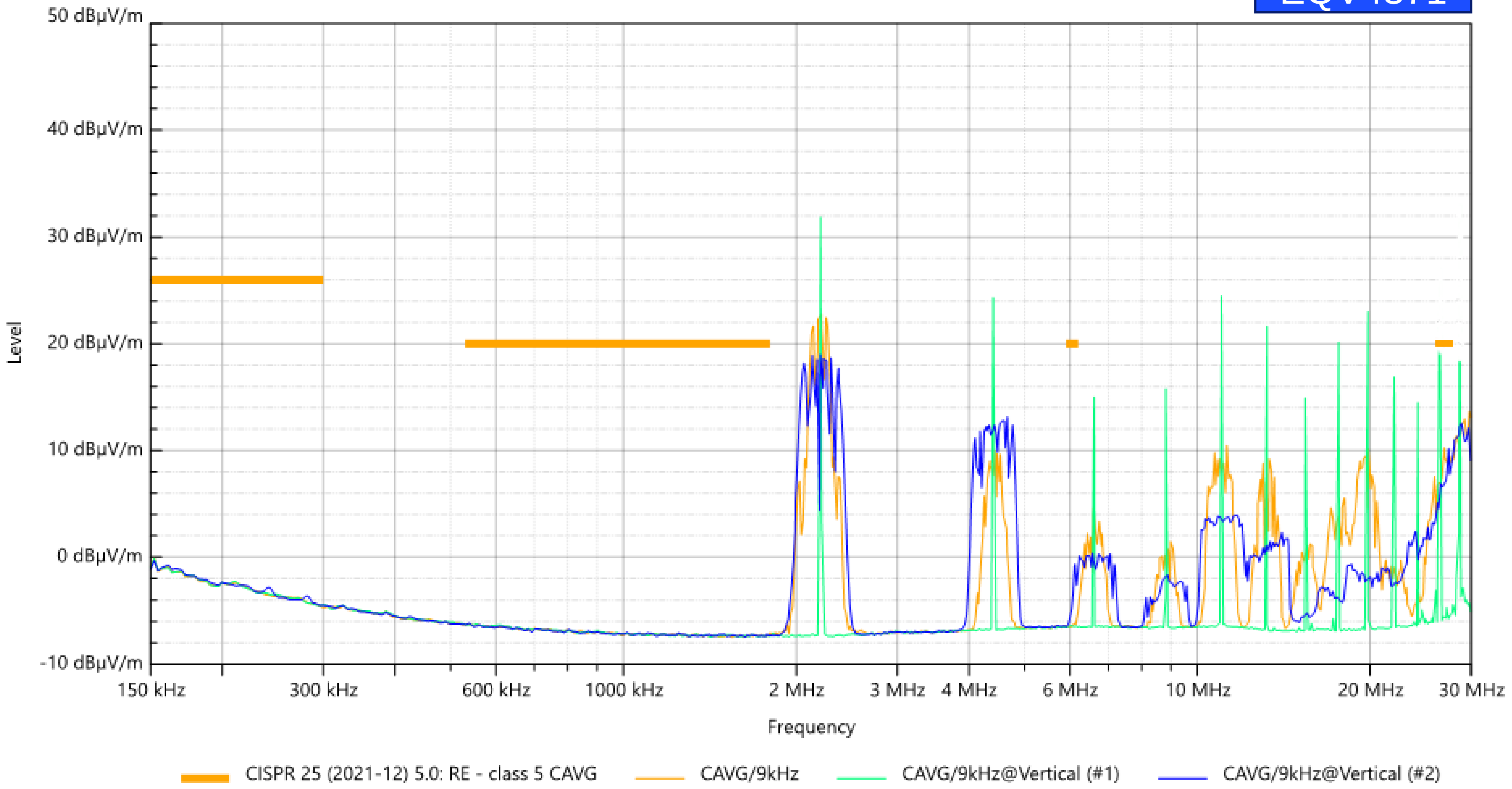
Carrier Frequency = 500kHz
Δf = 20% → 100kHz
FM → Sweep from 120kHz to 2kHz
Full Spectrum





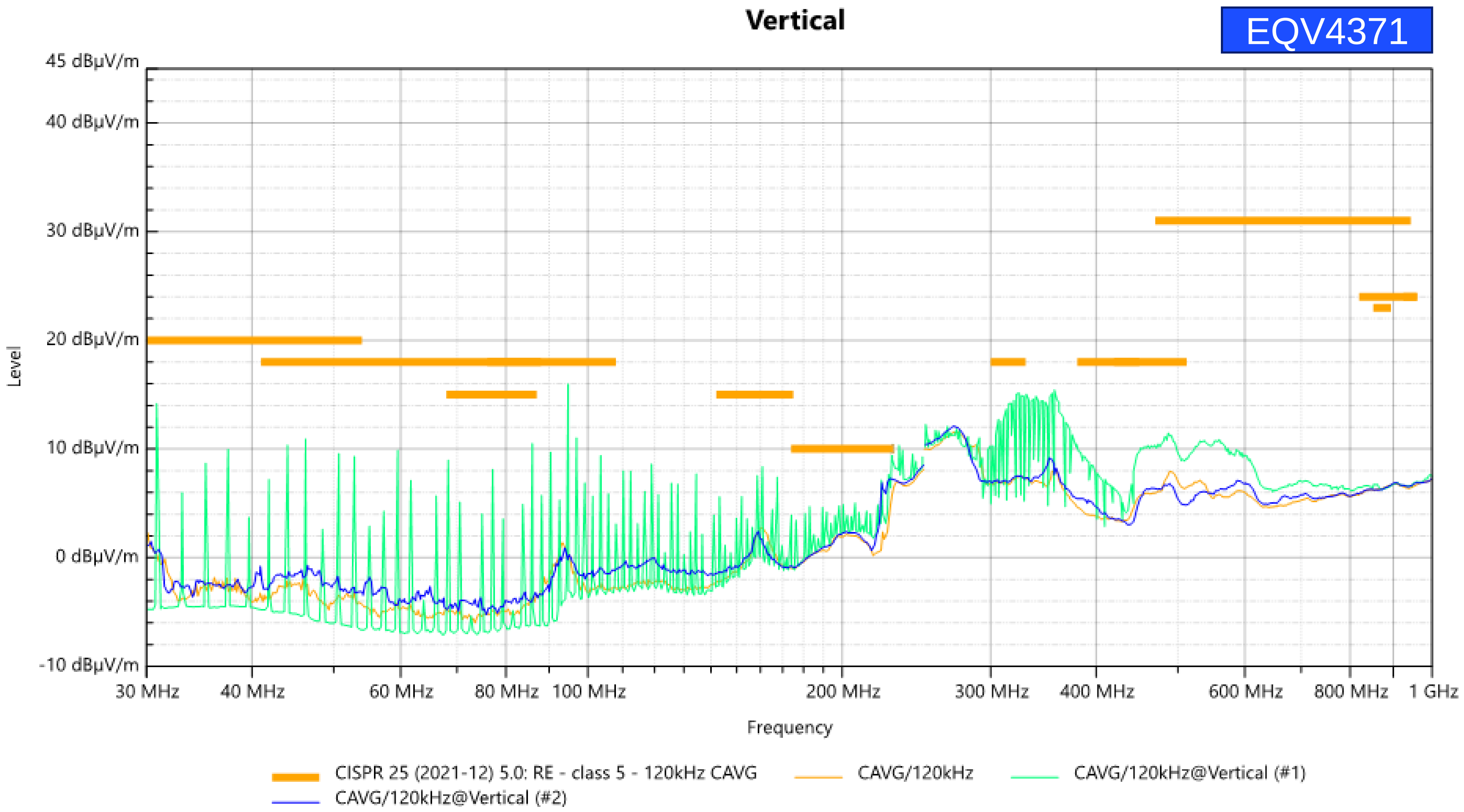
Bonus of „Dual FSS“

EQV4371



- The MPQ4371-AEC1 without FSS
- The MPQ4371-AEC1 with 15kHz FSS and a ±10% span (blue trace)
- The MPQ4371-AEC1 with dual-FSS: 15kHz FSS and a ±6.2% span, and 120kHz FSS with a ±2.5% span (yellow trace)

Bonus of „Dual FSS“



- The MPQ4371-AEC1 without FSS
- The MPQ4371-AEC1 with 15kHz FSS and a ±10% span (blue trace)
- The MPQ4371-AEC1 with dual-FSS: 15kHz FSS and a ±6.2% span, and 120kHz FSS with a ±2.5% span (yellow trace)

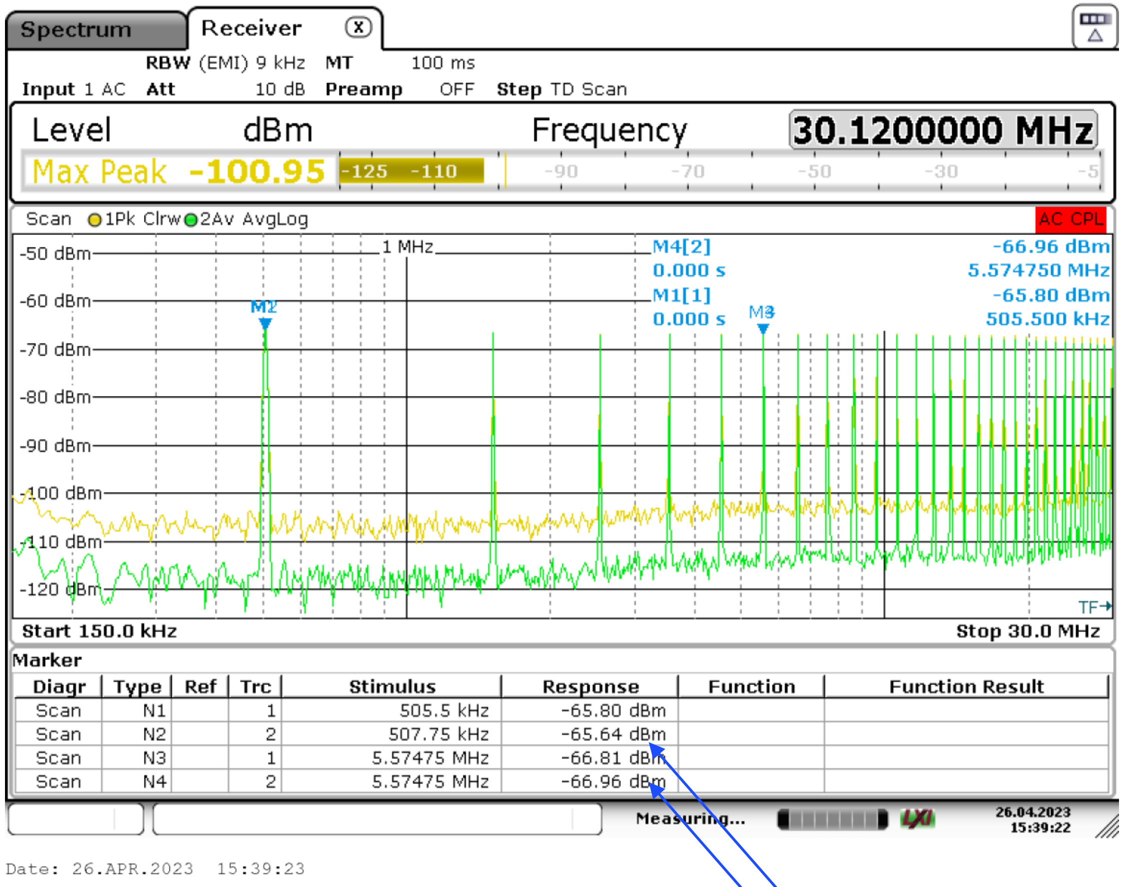
Practical Measurements with EMI Receiver

What Is the Effect on the Measurement Receiver?

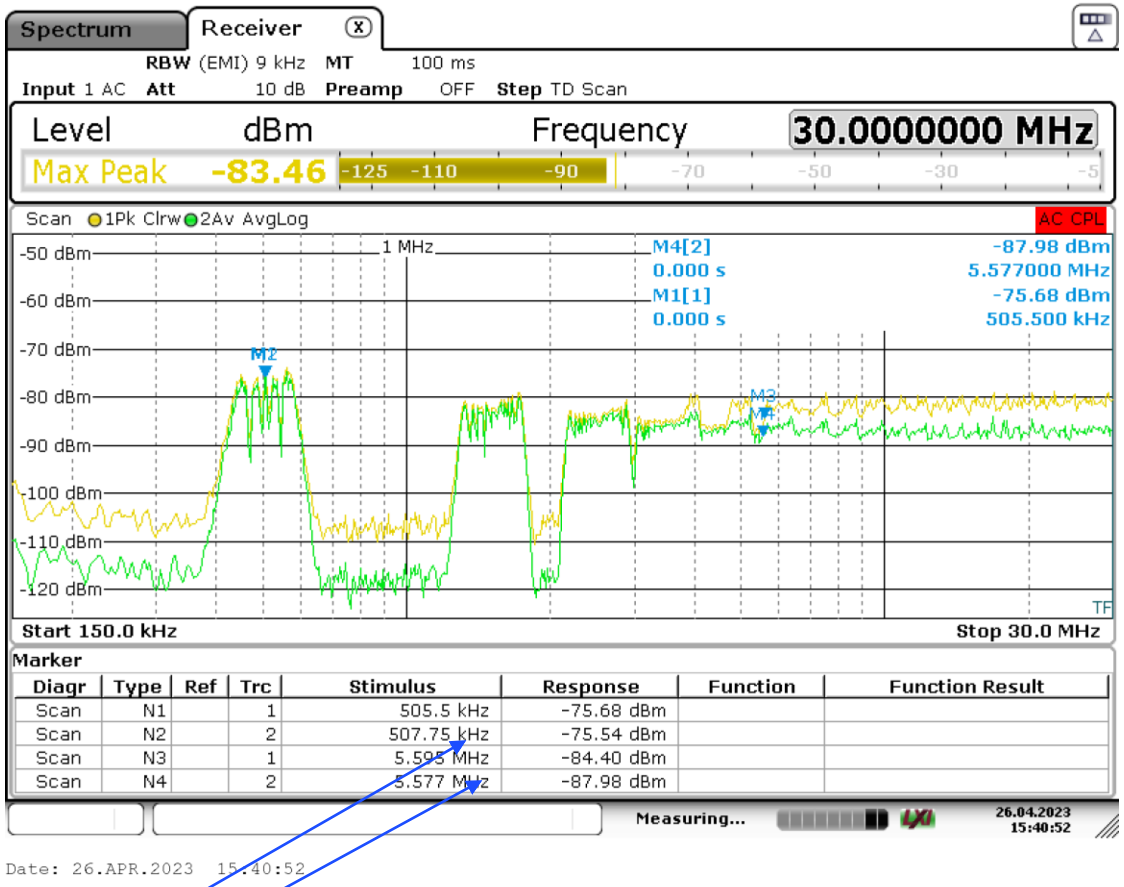
Carrier Frequency = 500kHz
Δf = 20% → 100kHz

FM → 9kHz
Modulation Waveform: Triangle

For reference



Modu-
lation
ON

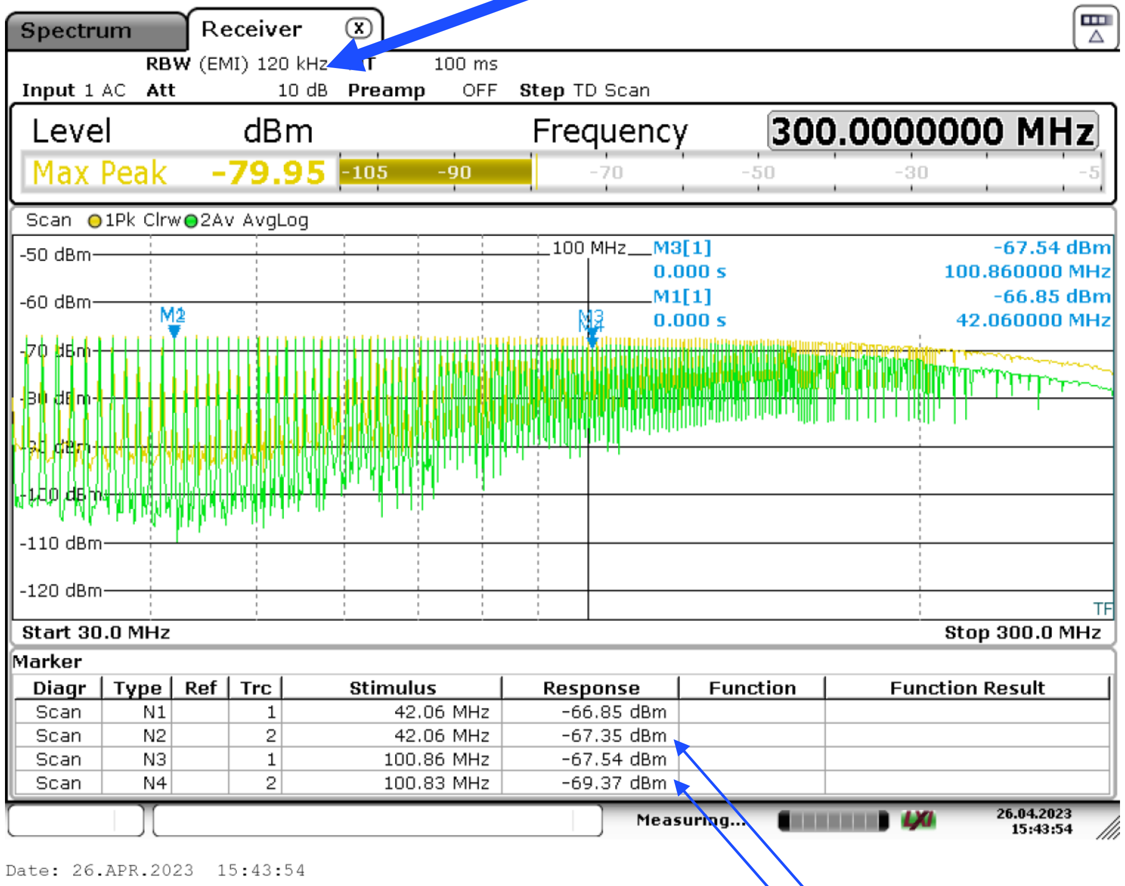


10dB to 20dB Attenuation

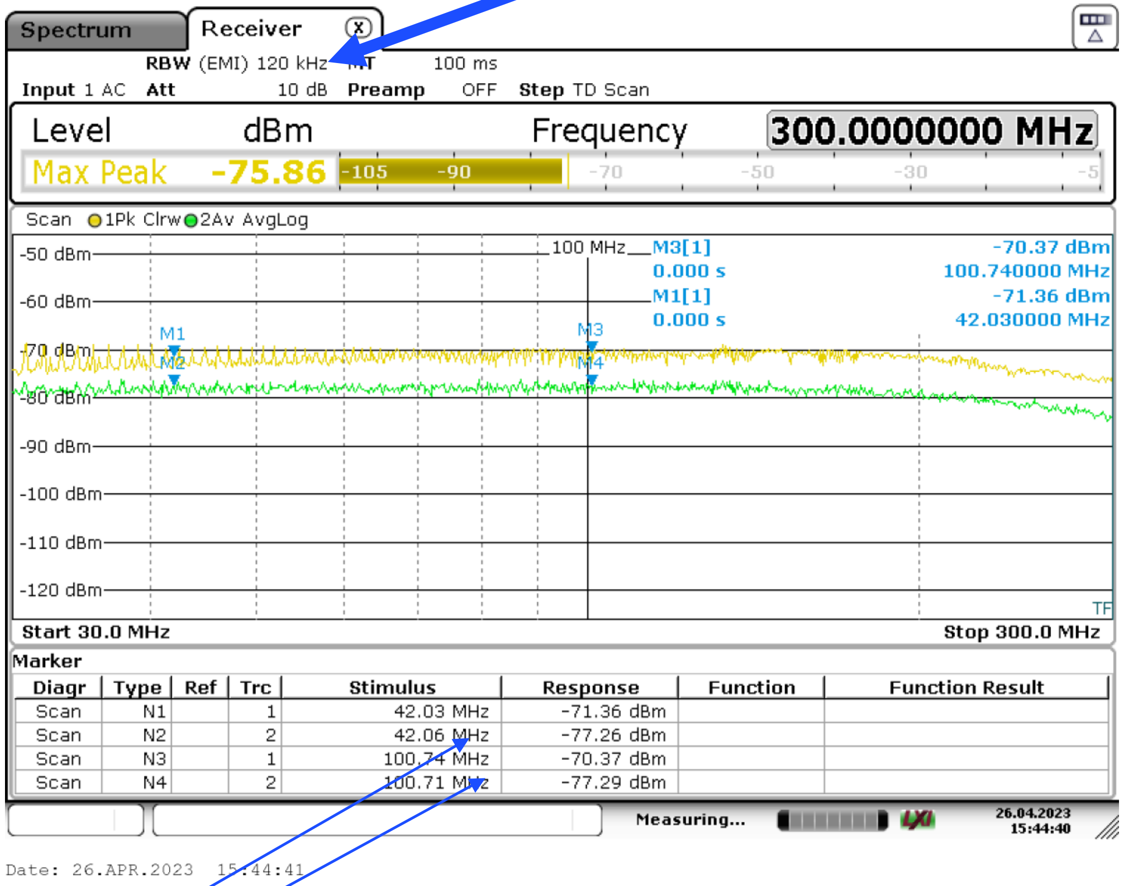
What Is the Effect on the Measurement Receiver?

Carrier Frequency = 500kHz
Δf = 20% → 100kHz

FM → 9kHz
Modulation Waveform: Triangle



Modu-
lation
ON

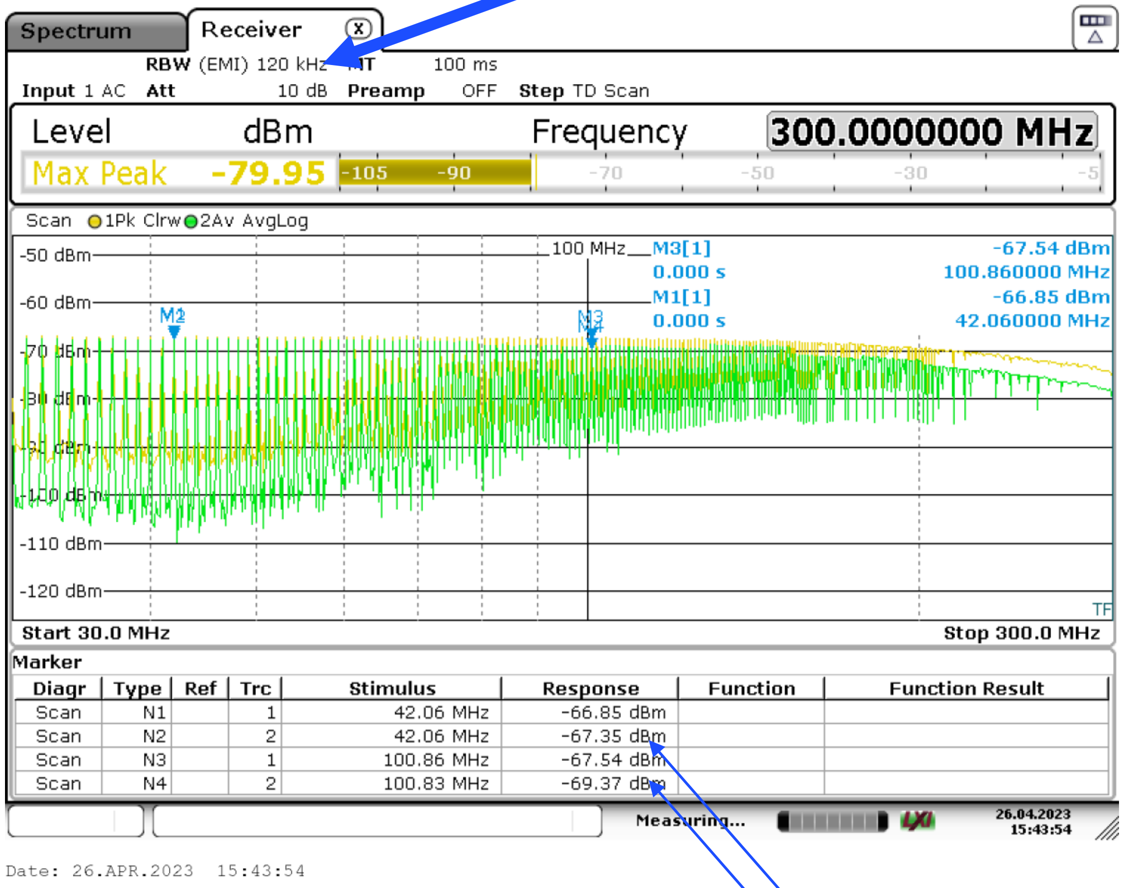


5dB to 10dB Attenuation

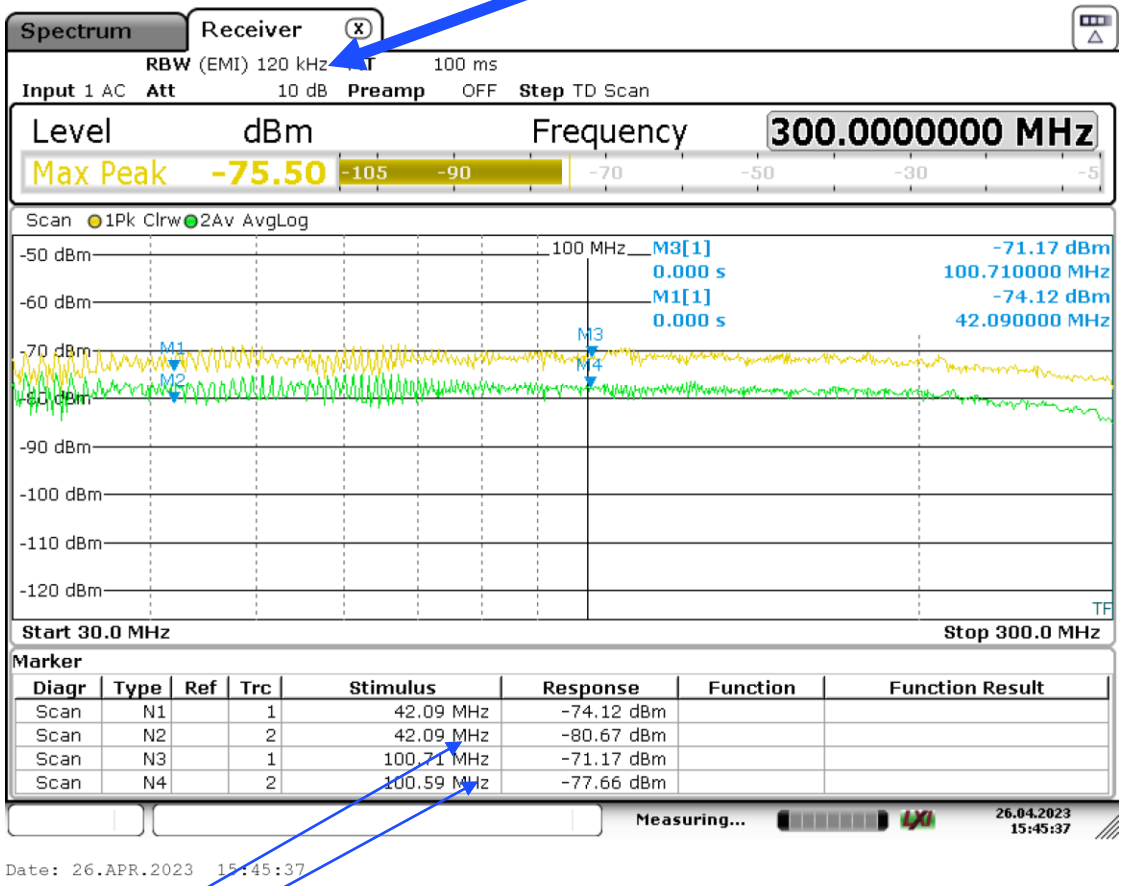
What Is the Effect on the Measurement Receiver?

Carrier Frequency = 500kHz
Δf = 20% → 100kHz

FM → 120kHz
Modulation Waveform: Triangle



Modu-
lation
ON



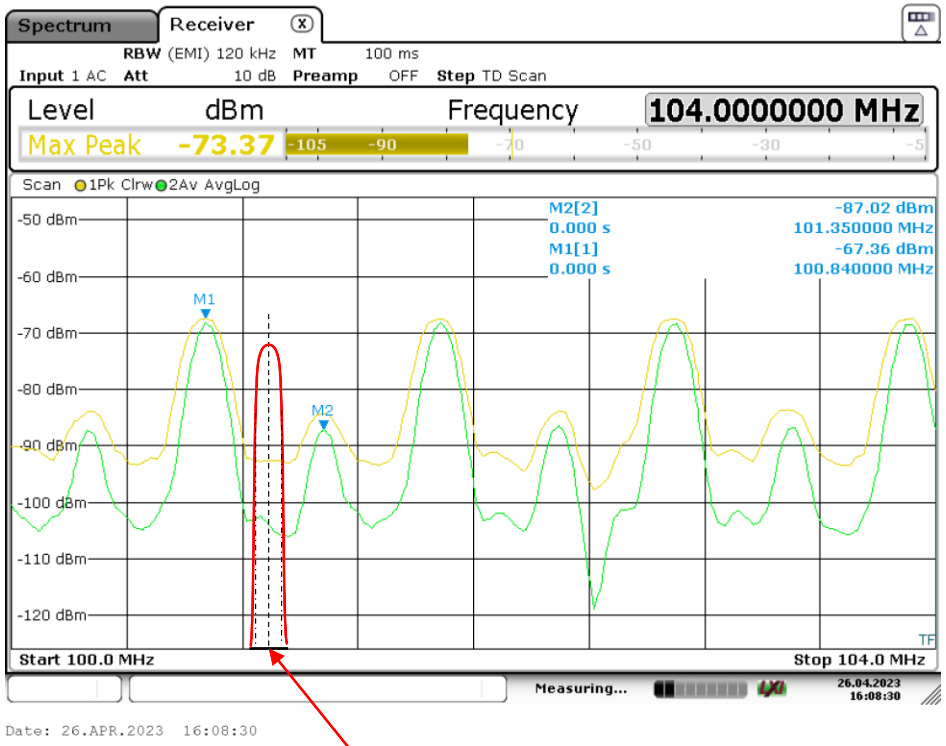
10dB to 20dB Attenuation

Limitations of Frequency Spread Spectrum

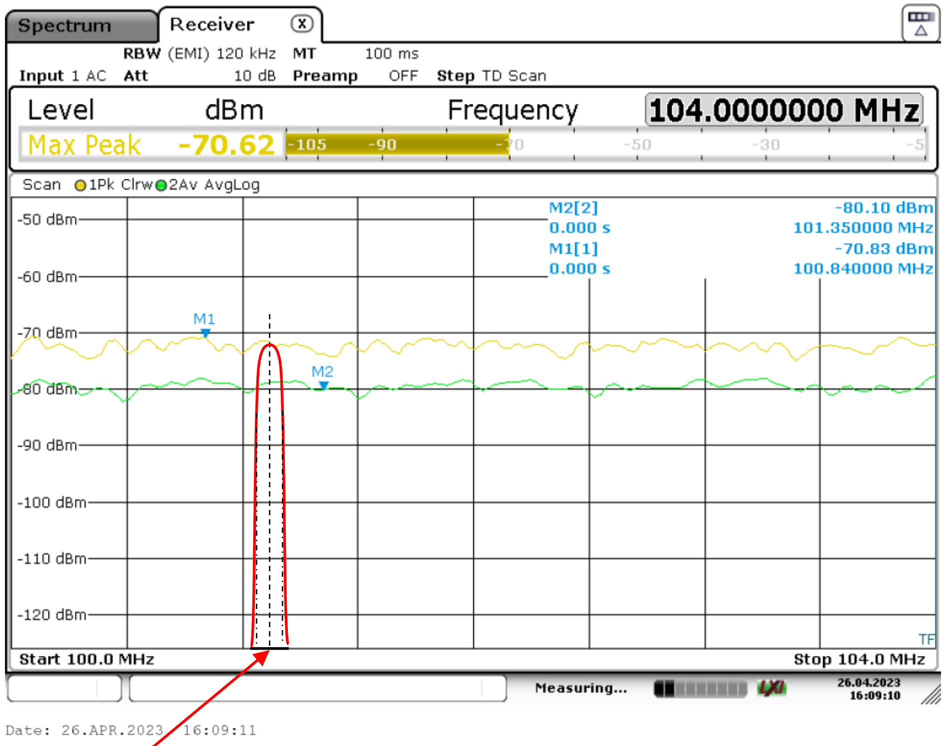
What Is the Effect for the End User?

1st

Carrier Frequency = 500kHz
Δf = 20% → 100kHz
FM → 120kHz
100MHz to 104MHz



Modulation ON



i.e. FM Radio Tuner

Attenuation ~ -20dB!

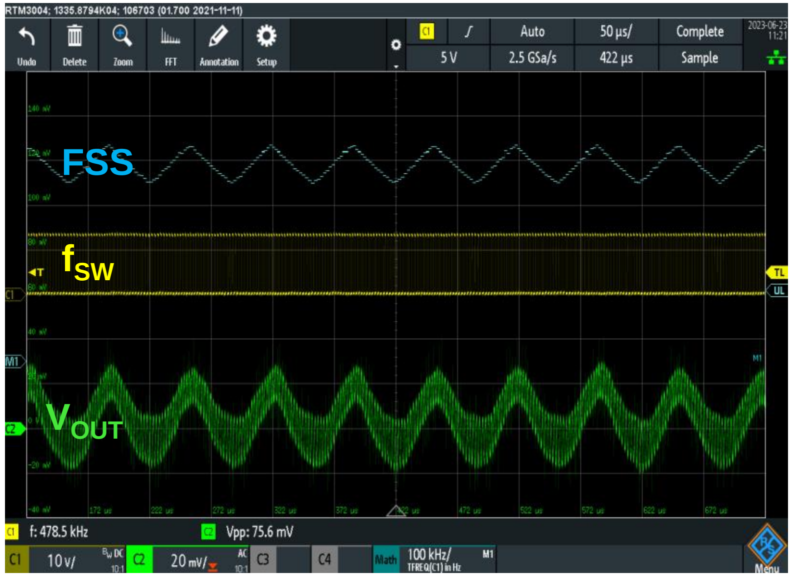
MPS

What Is the Effect for the End User?

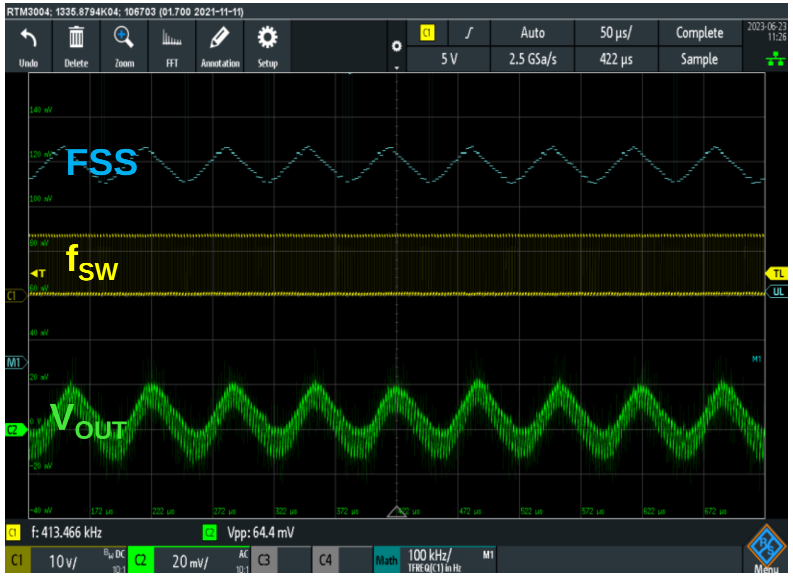
2nd

Depending on the inductance and the output capacitors, FSS can add a high voltage ripple to the output.

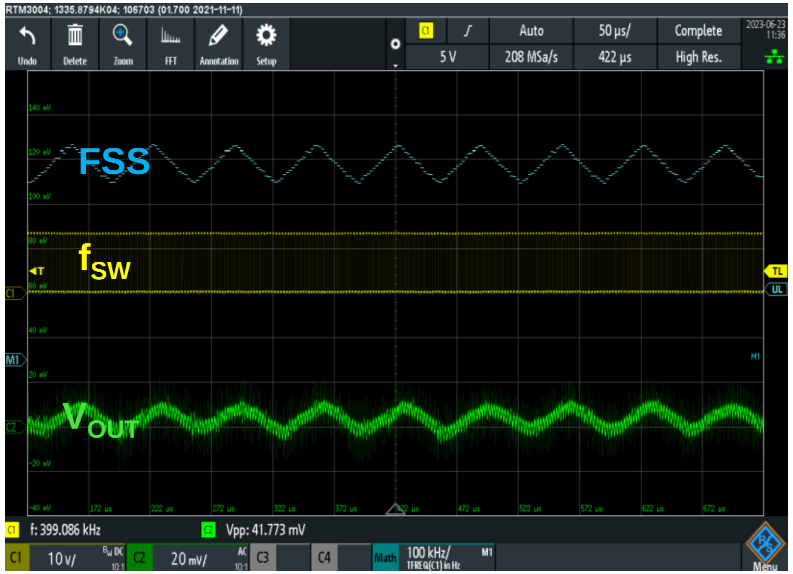
MPQ4323: f_{SW} = 470kHz, V_{IN} = 13V, V_{OUT} = 5V, I_{OUT} = 1A



L = 2.2µH, C_{OUT} = 2x 22µF 1210



L = 2.2µH, C_{OUT} = 4x 22µF 1210



L = 470nH, C_{OUT} = 4x 22µF 1210

V_{PP} = 75mV → V_{PP} = 65mV → V_{PP} = 40mV

How to Implement FSS

1st → Buy an SMPS that has FSS

e.g. MPQ4320 Series
or MPQ4340 Series

Most of the time, the development of the ECU is mostly finished and changing the SMPS will influence many technical parameters, as well as the timing of development.

2nd → If you have an SMPS with a frequency pin, it is possible to add an external FSS to only that pin.

How to Implement FSS

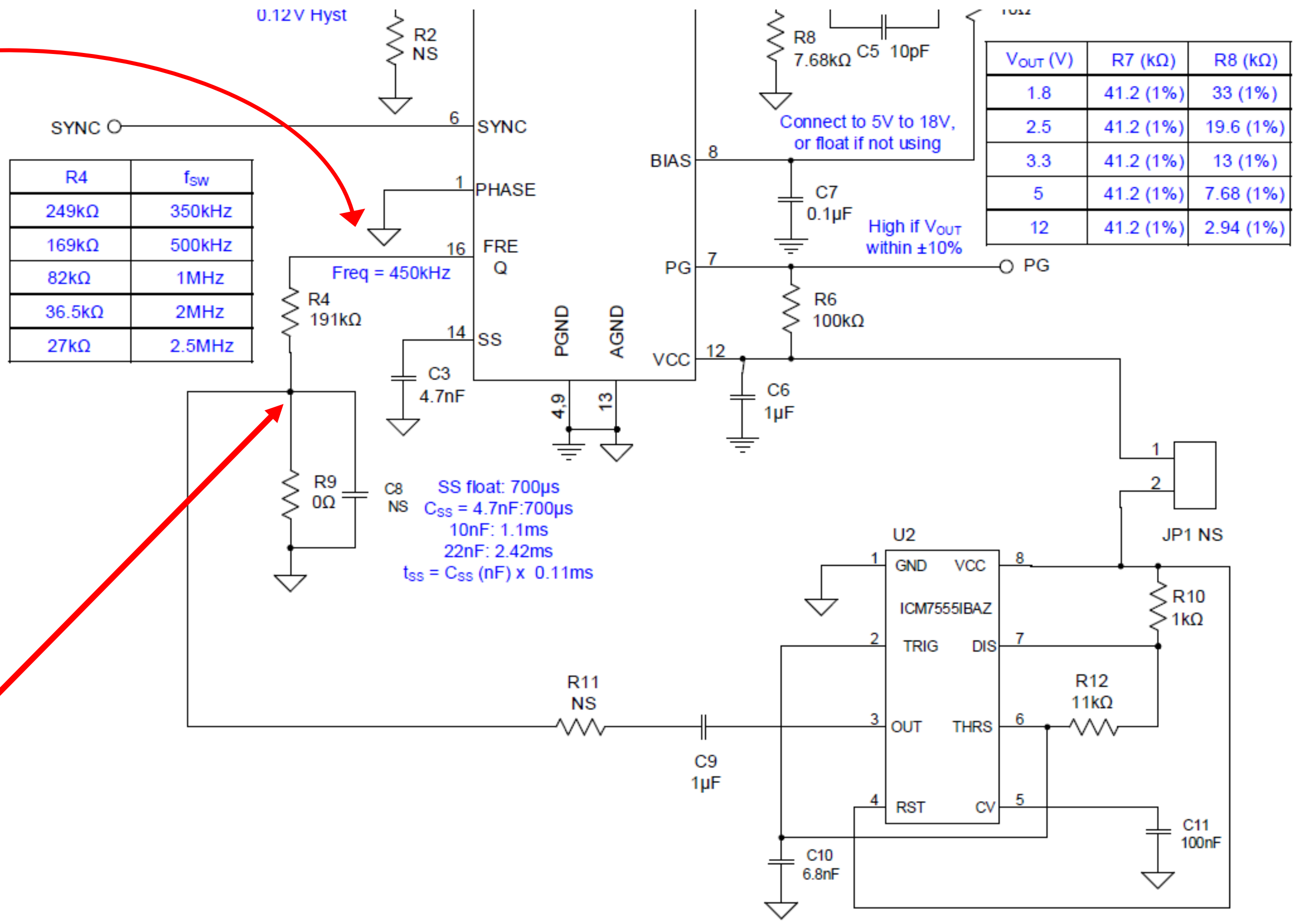
2nd → If you have an SMPS with a frequency pin, it is possible to add an external FSS to only that pin → e.g. MPQ4430

Here, the frequency pin (FREQ) has: 480mV @ 500kHz

→ We want to have a modulation depth of 20%

→ This means we have to change the voltage on FREQ about 120mV

→ **±60mV**



R4	f_{SW}
249kΩ	350kHz
169kΩ	500kHz
82kΩ	1MHz
36.5kΩ	2MHz
27kΩ	2.5MHz

V_{OUT} (V)	R7 (kΩ)	R8 (kΩ)
1.8	41.2 (1%)	33 (1%)
2.5	41.2 (1%)	19.6 (1%)
3.3	41.2 (1%)	13 (1%)
5	41.2 (1%)	7.68 (1%)
12	41.2 (1%)	2.94 (1%)

Calculating the Values

To get a very quick idea of the size of your components without spend hours of work solving complex differential equations, use the (very, very rough) equation below:

If $\boldsymbol{X_{C1} \ll R2}$, this current flows into C1

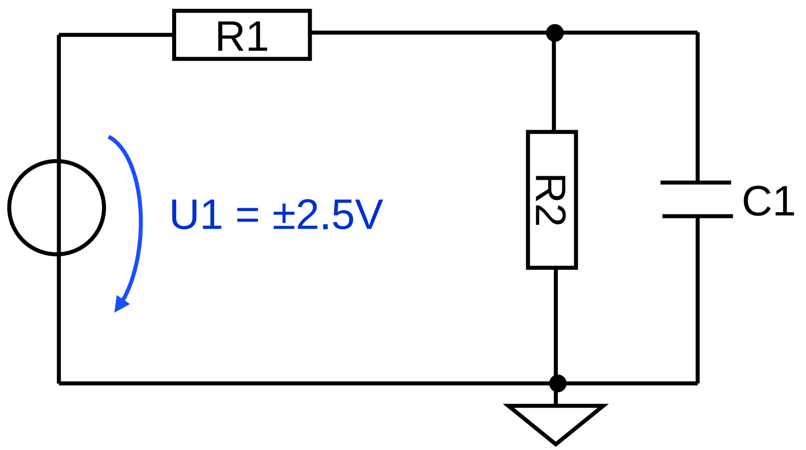
With: $R2 = 1k\Omega$

$FM = 9kHz$

$\Delta U = 120mV$

$$X_{C1} = \frac{1}{2 * PI * FM * C1} \approx 100\Omega$$

$$C1 \approx 176nF \rightarrow Selection\ 100nF$$



If ***R1 >> R2||C1***, R1 defines the main current of the circuit

Calculating the Values

If X_{C1} **<< *R2***, this current flows into C1

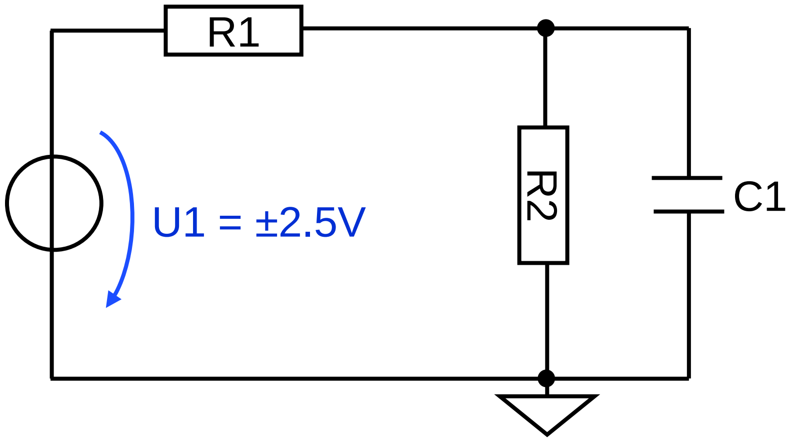
With: $R2 = 1k\Omega$

$FM = 9kHz$

$\Delta U = 120mV$

$$X_{C1} = \frac{1}{2 * PI * FM * C1} \approx 100\Omega$$

$$C1 \approx 176nF \rightarrow Selection\ 100nF$$



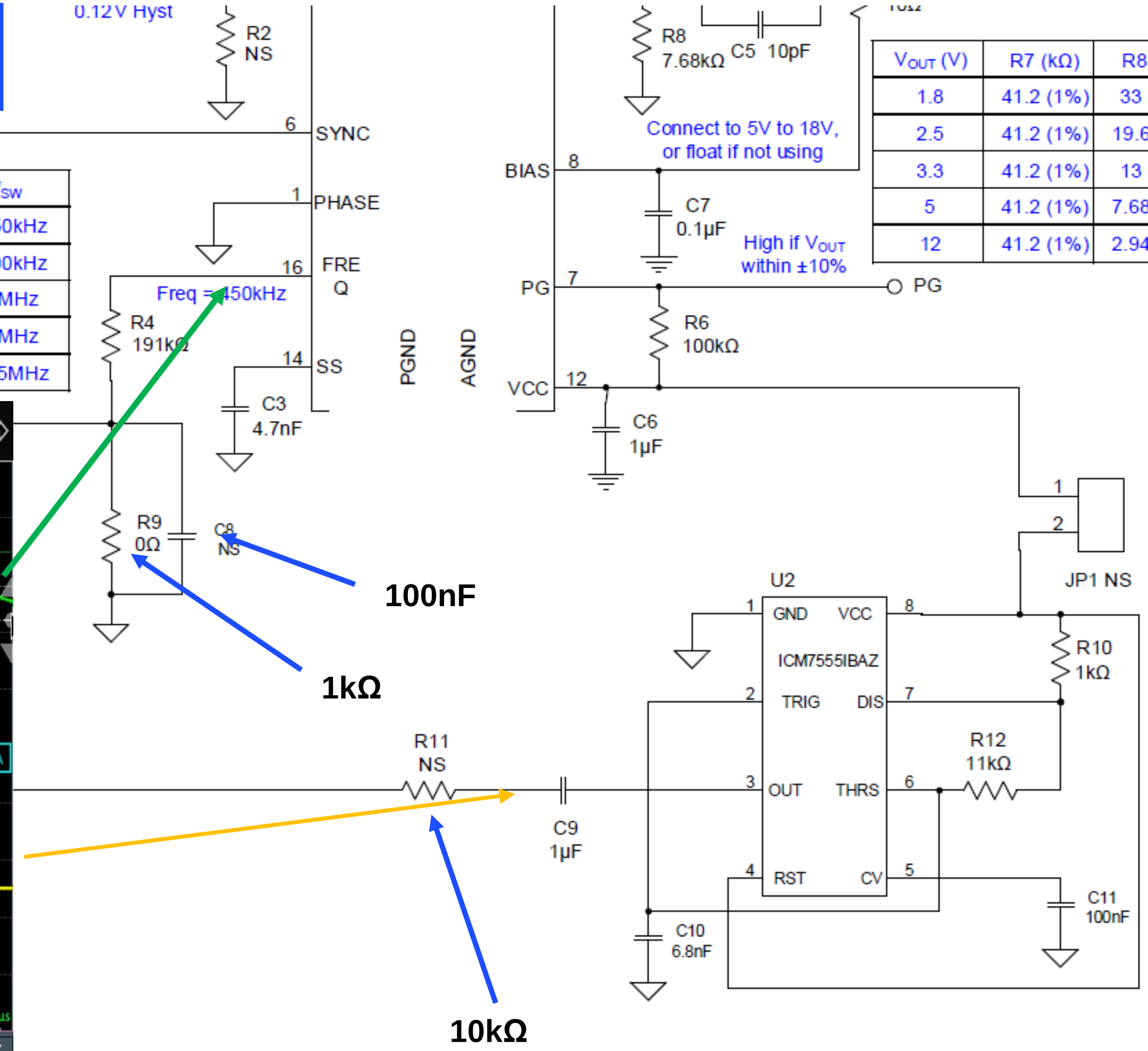
If ***R1 >> R2||C1***, R1 defines the main current of the circuit

$$\Delta U \approx \frac{I_{R1} * t}{C1} \approx \frac{\frac{U1}{R1} * \frac{1}{2 * FM}}{C1}$$

$$R1 \approx 11574\Omega \rightarrow Selection\ 10k\Omega$$

U1 must be calculated with 2.5V, as we are oscillating between +2.5V and -2.5V.

How to Implement FSS



R4	f_{SW}
249kΩ	350kHz
169kΩ	500kHz
82kΩ	1MHz
36.5kΩ	2MHz
27kΩ	2.5MHz

V_{OUT} (V)	R7 (kΩ)	R8 (kΩ)
1.8	41.2 (1%)	33 (1%)
2.5	41.2 (1%)	19.6 (1%)
3.3	41.2 (1%)	13 (1%)
5	41.2 (1%)	7.68 (1%)
12	41.2 (1%)	2.94 (1%)

Conclusion

- Frequency spread spectrum (FSS) does have many benefits that can effectively hide the EMI emissions of your design in “unused” areas
- FSS can not truly reduce the EMI emissions of the design
  - FSS just moves the energy from a single frequency band into neighboring bands
- Be careful when using FSS in a specific frequency area and take care regarding other frequency bands
- Depending on the values of the external components (e.g. the power inductor and output capacitors), FSS may add a voltage ripple to the output voltage

Q&A