# RF SAMPLING SOFTWARE-DEFINED RADIO FOR HF BAND

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## ABSTRACT

We propose a 1 - 30 MHz Software Defined Radio (SDR) with high-speed (100MHz) RF sampling.

The SDR has a very high sensitivity (8dB NF), high IP3 (+23dBm) and 130dB blocking Dynamic range (150Hz band width (BW)). This SDR has 2 receiving channels for wideband (1.25MHz to 10MHz) and narrowband (150Hz to 500kHz). This receiver does not have analog mixers, nor synthesizers nor analog AGC circuits.

We propose an appropriate Noise Figure (NF) calculation in the digital section in order to achieve very high sensitivity. We also propose a very high performance analog front-end in order to keep very high IP3 and IP2. Thereby, this SDR has been able to achieve high performance reception with narrowband filtering from 150Hz to 500kHz at an oversampled rate of 100MHz. This SDR also supports various demodulation types, such as DSB, USB, LSB, ISB, CW and Narrow FM.

## 1. INTRODUCTION

We designed an actual software based digital HF receiver (SDR) for both conventional communication and applied digital communication with RF sampling technique.

There are two channels on this receiver. One is narrowband for voice and conventional communication. This channel supports linear phase narrowband band-pass filters from 150Hz to 500 kHz, various demodulators, such as CW SSB ISB DSB FM, digital base band IQ data output, and analog voice output. The second channel is wideband for applied digital communication. This channel supports linear phase wideband band-pass filters from 1.25MHz to 10MHz and digital base band IQ data output. FFT function is also supported on both narrowband and wideband channels.

HF receivers are still widely used in many fields, for example in military and amateur radio. Therefore the modern commercial SDR for HF band should have easily adjustable and flexible parameter configuration and high capability for various receiving.

The most important performance characteristics of a receiver are sensitivity and dynamic range. The NF and the 2nd and 3rd order IPs (IP2, IP3) are excellent measures that generally can be covered to any required specification for these characteristics.

Compared with conventional SDR for HF band (like IF DSP based SDR), the RF sampling SDR has difficulty to keep its sensitivity (NF) because of the location of A/D converter (ADC). On the conventional SDR for HF, ADC is located far from the RF input and there is 50dB RF gain or more from RF input to ADC, so, there was no big issue to keep the SDRs NF. However, on the RF sampling SDR, the ADC is very close to RF input and there is only 20～30dB RF gain from RF input to ADC. That means it is very important to keep SDRs NF for its design.

This paper is focused on the hardware platform of SDR for HF. In order to build a high-performance SDR for HF, we explain how to keep and verify the SDRs NF, IP3 and IP2.

## 2. SENSITIVITY (NF) FOR HF

As we mentioned earlier, SDR for HF is used to receive very weak CW signals through to very high power broadcasting signals with very narrow band width (BW) and applied digital communication with wide BW at the same time. An important approach in the system design is how to keep such a narrow BW sensitivity.

The high-performance HF receiver should have 8～9dB NF and more than +20dBm IP3 in the high sensitivity mode. It should also have 14～15dB NF and more than +30dBm IP3 in the low distortion mode. That means Minimum Detectable Signal (MDS) @150Hz BW is about -144dBm, whereas the strongest broadcasting signal in RF input is up to -20dBm. Therefore the SDR should have 120dB or more linear signal handling capability on it. The IP3 and IP2 problem is a little easier than the NF problem because in the digital section post-ADC, there is almost no distortion generated and it is good enough to keep receivers IP3 and IP2.

If we think about 120dB or more linear signal handling capability, it is not a good idea to use analog AGC circuit ahead of the ADC section. The AGC circuit compresses RF input if some strong signals are in the receiving band and it reduces the sensitivity of weak signals. Thanks to the high sampling rate and appropriate decimation technique, it is possible to have 120dB or more linear signal handing capability with no analog AGC circuit even though this uses the popular 16bit ADC.

With reference to the hardware design it should be noted that the calculation of NF is important to keep the performances of the SDR.

## 3. ANALYSIS OF NF

The NF of the receiver is determined by the ADC NF, Digital signal processing error, and the analog front-end's NF. Hence, in this section, we analyze the Noise Figure of these respectively.

### 3.1 NF Analysis for ADC

For example, the performance characteristics of ADC are shown as figure (1).

| | |
|---|---|
| Resolution [bits] | 16[ bits] |
| Full-scale input swing voltage [V p-p] | 2.75[V p-p] |
| Sampling frequency [MHz] | 100[MHz] |
| Signal to quantization noise ratio S/N [dB] | 81.1[dB] |

Figure (1) Performance characteristics of ADC

Amount of noise in ADC output can be described as:

$$\begin{aligned}&\text{Amount of noise in ADC output[dBFS]}\\&\quad = -S/N = -81.1[\text{dBFS}] \quad (1)\end{aligned}$$

This amount of noise in ADC has a nyquist bandwidth of 50MHz.
Further, the amount of noise in 1Hz BW of ADC output can be described as:

$$\begin{aligned}&\text{Amount of noise in 1Hz BW of ADC output[dBFS]}\\&\quad = \text{Amount of noise in ADC output[dBFS]}\\&\quad - \text{Correction factor for 1Hz BW [dB]} \quad (2)\end{aligned}$$

Correction factor for 1Hz BW is:

$$\begin{aligned}&\text{Correction factor for 1Hz Bandwidth [dB]}\\&\quad = 10\log(\text{Nyquist bandwidth / 1Hz bandwidth})\\&\quad = 10\log(5e7) = 77.0[\text{dB}] \quad (3)\end{aligned}$$

Hence, from (2),

$$\begin{aligned}&\text{Amount of noise in 1Hz BW of ADC}\\&\quad = -81.1[\text{dBFS}] - 77[\text{dB}]\\&\quad = -158.1[\text{dBFS/Hz}] \quad (4)\end{aligned}$$

To convert to the RF level [dBm]

Assuming that all transmission lines are designed for 50 ohm in this calculation,
Full-scale voltage is specified as:

$$\text{Full-scale voltage} = 2.75[\text{Vp-p}] = 12.8[\text{dBm}] = 0[\text{dBFS}] \quad (5)$$

By using equation (4), (5)
Amount of noise in 1Hz BW of ADC output can be converted to the RF level:

$$\begin{aligned}&\text{Amount of noise in 1Hz BW of ADC output}\\&\quad = 12.8[\text{dBm}] - 158.1[\text{dB}] = -145.3[\text{dBm}] \quad (6)\end{aligned}$$

On the other hand, thermal noise in 1Hz BW is given by:

$$\begin{aligned}&\text{Thermal noise in 1Hz BW} = kT\\&\quad = (1.38e-23)\cdot(2.98e2) = 4.11e-21[\text{W/Hz}]\\&\quad = 4.11e-18[\text{mW/Hz}] \quad (7)\end{aligned}$$

Where k = Boltzmann's constant, 1.38e-23
T = absolute temperature, K (298 K)

Convert this to [dBm] unit:

$$10\log kT = 10\log(4.11e-18) = -173.9[\text{dBm/Hz}] \quad (8)$$

ADC has no gain because ADC only works with the converter analog to digital. So, degradation of the noise in 1Hz BW is almost equal to NF of ADC.

Therefore, NF of ADC is designated as:

$$\begin{aligned}&\text{NF of ADC} = \frac{\text{ADC Noise component in 1Hz BW}}{\text{Thermal noise in 1Hz BW}}\\&\quad = -145.3[\text{dBm}] - (-173.9[\text{dBm}]) = 28.6[\text{dB}] \quad (9)\end{aligned}$$

From equation (9), the NF of ADC can be assumed to be 28.6dB.

### 3.2 Analysis of appropriate data bit length for digital signal processing (DSP)

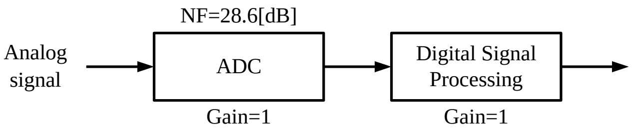



Figure (2) Process of Digital Signal Processing

Prevailing noise in the digital signal processing section is quantization-noise and output data length of each process. In order to achieve designs for very narrowband filters with very high sampling rate, we employ two kinds of decimator block made by a combination of CIC decimation filter and CIC compensation filter as a decimation filter to avoid huge filter orders and hence complexity.

An important process for NF calculation in digital signal processing is shown in figure (3)


Figure (3) main stream about digital signal processing

We calculate several patterns of NF calculations in the digital signal processing section. At each filter block in figure (3), amount of noise in each filter is described as equation (10) to (12):

In-band noise of the filter
= in-band noise of ADC output
+ quantization-noise of itself (10)

Out-band noise of the filter
= out-band quantization-noise of it (11)

Amount of noise in the filter output
= in-band noise of the filter
+ out-band noise of the filter (12)

Hence, the noise of each filter depends on the quantization-noise of itself.

We show the NF of ADC plus DSP in the case of the different length of bit for decimation filters and FIR filters to clarify the reduction of the NF between NF for ADC only and NF for ADC+DSP. Calculation Results are shown in figure (4) to figure (9).

Figure (4) shows if 16bit length is used for both decimation filter and FIR filter, that is not good enough to keep ADC NF of 28.6dB.

Decimation filters bit length: 16bit
FIR filters bit length: 16bit

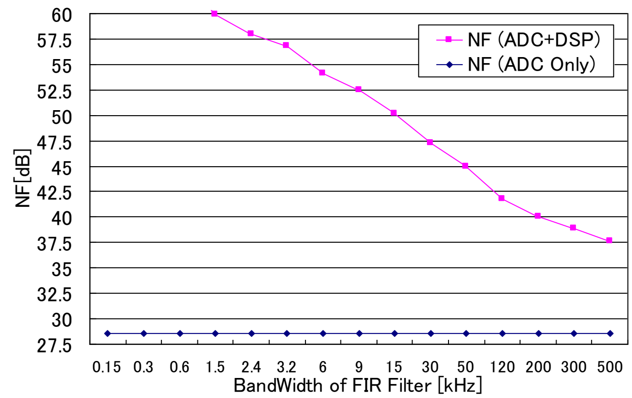



Figure (4) NF calculation of 16bit decimation filter and 16bit FIR filter

To calculate the good length of bit for decimation filters, FIR filters bit is fixed by 32bit.

Decimation filters bit length: 16bit
FIR filters bit length: 32bit

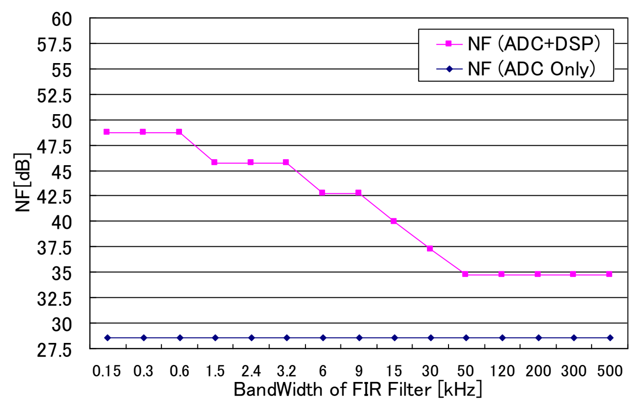



Figure (5) NF calculation of 16bit decimation filter and 32bit FIR filter

Figure (5) shows that 16bit for decimation filter is not good enough to keep ADC NF.

Decimation filters bit length: 22bit
FIR filters bit length: 32bit

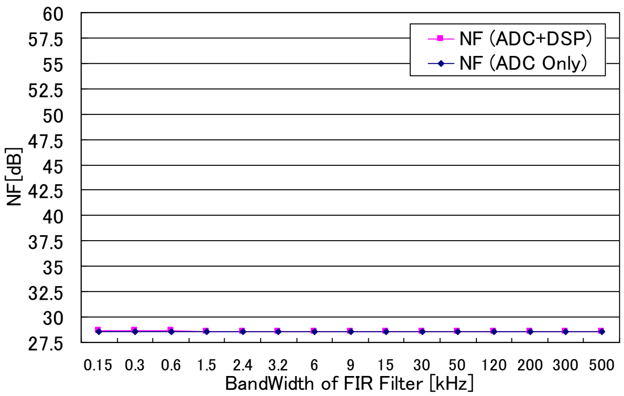



Figure (6) NF calculation of 22bit decimation filter and 32bit FIR filter

From figure (6), Decimation filters bit length of 22bit is good enough to keep the ADC NF.

Then, to calculate the good length of the bit for FIR filter, decimation filter bit is fixed by 32bit.

Decimation filter bit length: 32bit
FIR filter bit length: 22bit

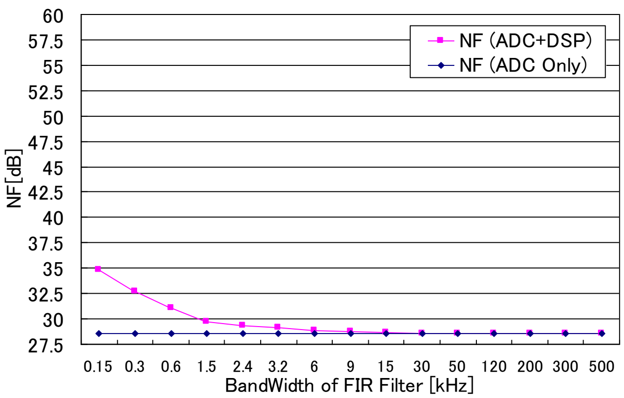



Figure (7) NF calculation of 32bit decimation filter and 22bit FIR filter

Figure (7) shows that 22bit for FIR filter is not good enough to keep ADC NF.

Decimation filter bit length: 32bit
FIR filter bit length: 25bit

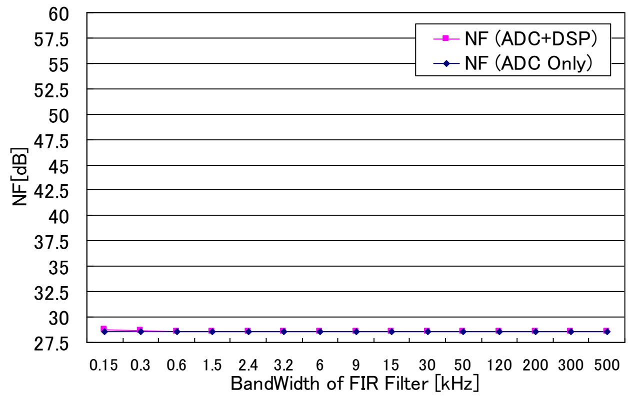



Figure (8) NF calculation of 32bit decimation filter and 25bit FIR filter

From figure (8), FIR filters bit length of 25bit is good enough to keep the ADC NF.

We confirm this calculation by using the 22bit decimation filter and 25bit FIR filter in figure(9)

Decimation filter bit length: 22bit
FIR filter bit length: 25bit

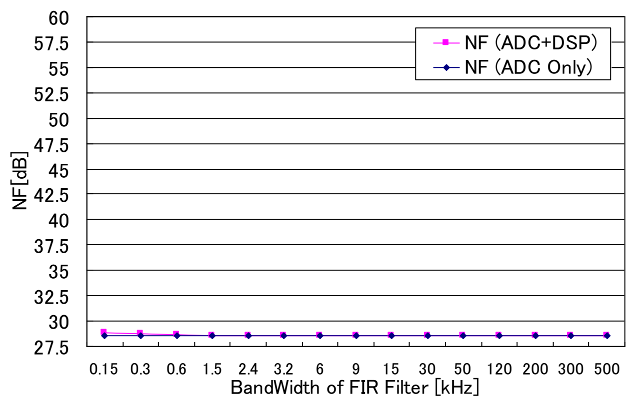



Figure (9) NF calculation of 22bit decimation filter and 25bit FIR filter

But for the convenience of digital signal processing, 24bit is better than 22bit and also 32bit is better than 25bit. Therefore, we chose to use 24bit length for decimation filter and 32bit length for FIR filter in this system.

### 3.3 NF Analysis and design for analog front-end

To design SDR for HF which has 8～9dB NF and +20dBm IP3, we also have to design appropriate analog front-end.

We calculated necessity of the NF for front-end in order to keep receivers NF of 8dB. Figure (10) is shown NF for front-end and necessary gain for it.

| NF for front-end [dB] | Necessary gain for front-end [dB] |
|---|---|
| 0 | 21.3434046 |
| 1 | 21.5605299 |
| 2 | 21.8502767 |
| 3 | 22.2448863 |
| 4 | 22.7988092 |
| 4.5 | 23.1642654 |
| 5 | 23.6146253 |
| 5.5 | 24.1826455 |
| 6 | 24.9232352 |
| 6.5 | 25.9393661 |
| 7 | 27.4622541 |
| 7.5 | 30.2297457 |

Figure (10) NF for front-end and necessary gain for it

From figure (10), we chose to design the front-end section which has 6dB NF and 25dB gain for realistic design and to keep a good receiver intercept point.

The basic schematic of new amplifier design is shown as figure (11). This amplifier has been using both current and voltage feedback. These types of amplifier can have simultaneously low input/output SWR together with moderate noise figure and high intercept point.

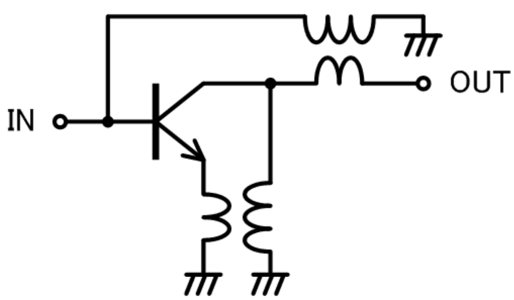


Figure (11) Basic schematic of the amplifier.

We have used a “push-pull” layout design of this amplifier as a base amplifier for the receiver front-end.

The base amplifier’s characteristics are shown as figure (12).

| | |
|---|---|
| Gain | 9.2dB @14MHz |
| NF | 3.7dB @14MHz |
| IP3in | 45.9dBm @14MHz |
| IP2in | 82.2dBm @14MHz |

Figure (12) Base amplifier characteristics

Each datum of this amplifier is shown from figure (13) to figure (15).

The NF and Gain of the base amplifier are shown as figure (13). The NF can be read around 3.7dB@14MHz and the gain can be read around 9.2dB@14MHz form this figure.

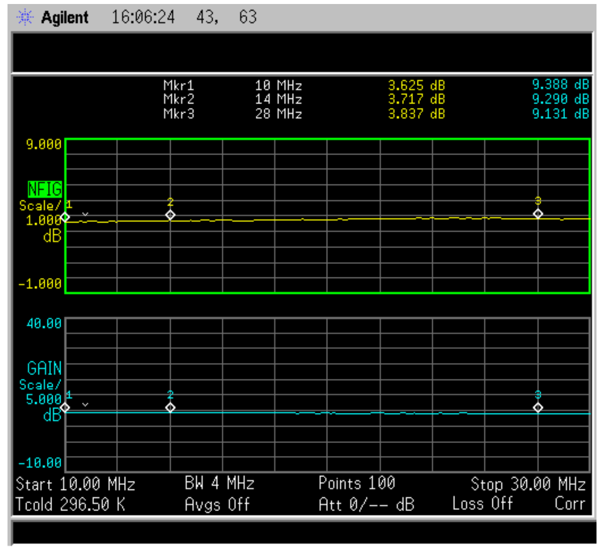
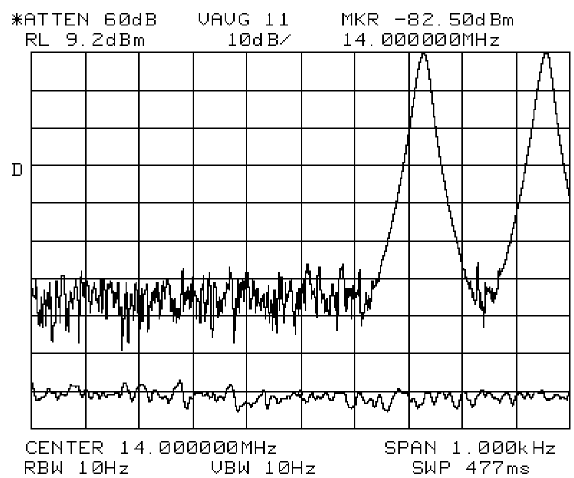


Figure (13) NF and gain of the base amplifier

The IP3 of the base amplifier is shown as figure (14).



14.05/14.10MHz 0dBm/ 2-tone input

Figure (14) IP3 of the base amplifier

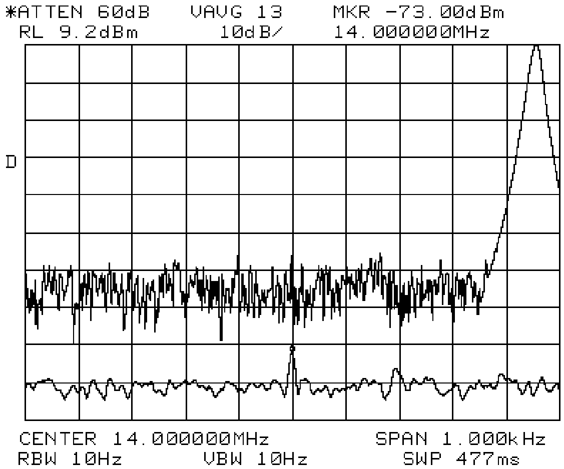
The IP3in can be found from:

The IP3in

$$= \frac{\text{Two tone level - IMD level}}{2} + \text{Intput} \quad (13)$$

$$= \frac{9.2[\text{dBm}]-(-82.50[\text{dBm}])}{2} + 0[\text{dBm}] = 45.85\ [\text{dBm}] \quad (14)$$

The IP2 of the base amplifier is shown as figure (15)




14.10/28.10MHz 0dBm/ 2-tone input

Figure (15) IP2 of the base amplifier

The IP2in can be found from

The IP2in

$$= (\text{Two tone level} - \text{IMD level}) + \text{Intput} \quad (15)$$

$$= 9.2[\text{dBm}] - (-73.00[\text{dBm}]) + 0[\text{dBm}] = 82.2\ [\text{dBm}] \quad (16)$$

In order to get 25dB gain for the front-end, three base amplifiers are used in series for the receivers front-end as an RF amplifier.

Total performances of the RF amplifier are shown from figure (16) to figure (18).

The NF and Gain of the RF amplifier are shown as figure (16). The NF can be read around 4.1dB@14MHz and the gain can be read around 26dB@14MHz form this figure.

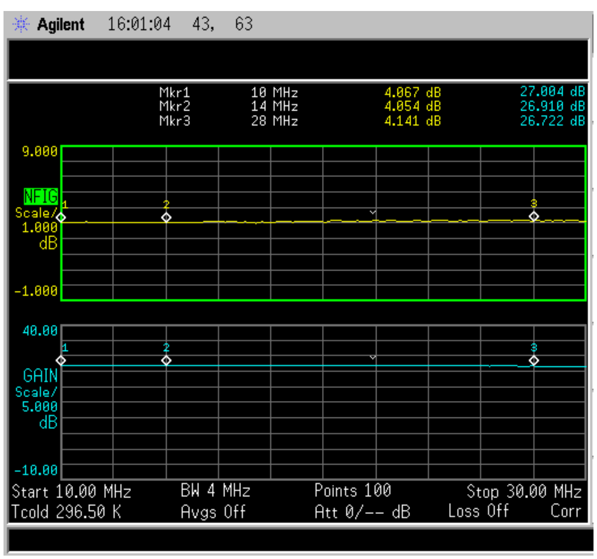
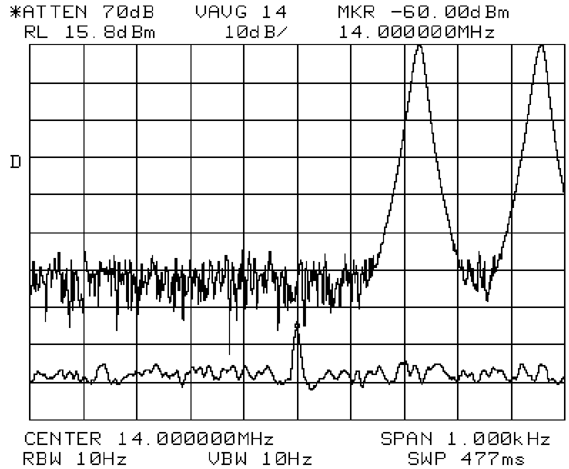



Figure (16) NF and gain of the RF amplifier

The IP3 of the RF amplifier is shown as figure (17).




14.05/14.10MHz -10dBm/ 2-tone input

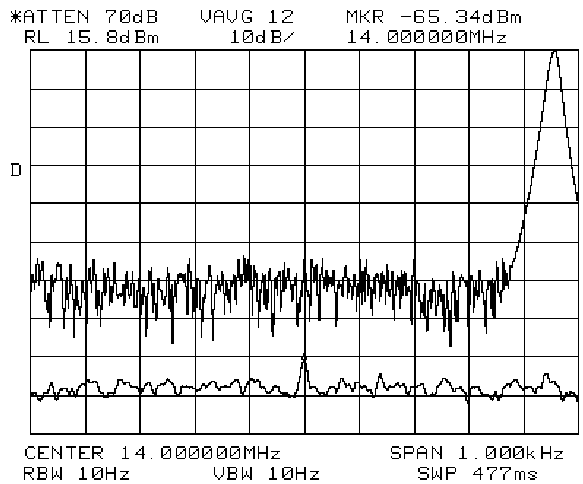
Figure (17) IP3 of the RF amplifier

The IP3in can be found from equation (13).

The IP3in

$$= \frac{15.8[\text{dBm}] - (-60.00[\text{dBm}])}{2} + (-10)[\text{dBm}] = 27.9\ [\text{dBm}] \quad (17)$$

The IP2 of the RF amplifier is shown as figure (18)




14.10/28.10MHz -10dBm/ 2-tone input

Figure (18) IP2 of the RF amplifier

The IP2in can be found from equation (15).

The IP2in

$$= 15.8[\text{dBm}] - (-65.34[\text{dBm}]) + (-10)[\text{dBm}] = 71.14\ [\text{dBm}] \quad (18)$$

The gain of the RF amplifier is calculated from:

Gain

$$= \text{Output} - \text{Input} \quad (19)$$

$$= 15.8 - (-10) = 25.8[\text{dB}] \quad (20)$$

The RF amplifier's characteristics are shown as figure (19).

| | |
|---|---|
| Gain | 25.8dB @14MHz |
| NF | 4.1dB @14MHz |
| IP3in | +27.9dBm @14MHz |
| IP2in | +71.1dBm @14MHz |

Figure (19) RF amplifier characteristics

We have used this amplifier in the RF front-end of this receiver and achieved about 26dB RF gain in this section to keep the receivers NF, IP3 and IP2.

## 4. Conclusion

We designed Software Defined Radio (SDR) for HF with high-speed (100MHz) RF oversampling. This SDR does not have analog mixers nor analog synthesizers nor analog AGC circuits.

We have achieved high sensitivity (8.0dB NF) and high IP3 (+23dBm) in high sensitivity mode. In low distortion mode (a pair of base amplifiers are used as an RF amplifier instead of a triad of base amplifiers), we have achieved 14.0dB NF and very high IP3 (+30dBm). We have also achieved 130dB blocking dynamic range in 150Hz BW. That means this SDR has 130dB linear signal handling capability for very narrow band reception.

The specification of the SDR for HF band is shown as below (figure 20).

| | |
|---|---|
| Frequency Range | 500kHz to 30MHz |
| NF (high sensitivity mode) | 8.0dB (typ) |
| NF ( low distortion mode) | 14.0 dB (typ) |
| IP3(in-band) (high sensitivity) | +23dBm (typ) |
| IP3(in-band) (low distortion) | +30dBm (typ) |
| IP2(in-band) (high sensitivity) | +70dBm (typ) |
| IP2(in-band) (low distortion) | +80dBm (typ) |
| Receiving band width (wide) | 1.25MHz to 10MHz |
| Receiving band width (narrow) | 150Hz to 500kHz |
| Signal linearity | >130dB |
| RF limit level for receiving | -13dBm |
| IQ data output (Max) | 24bit each |

Figure (20) Performance characteristics of the SDR for HF

## 5. REFERENCES

[1] Sabin and Schoenike, *HF Radio Systems and Circuit Revised 2nd Edition*

[2] Cotter W. SAYRE, *Complete Wireless Design*

[3] Rohde Whitaker, *Communications Receivers Third Edition*

ADC: A/D convertor
BW: Band width
dBFS: dB Full-scale
IMD: Intermodulation distortion.
IP3: The third-order intercept point.
IP2: The second-order intercept point.
IP3in: The third-order input intercept point.
IP2in: The second-order input intercept point.
MDS: Minimum detectable signals
NF: Noise figure