

## AP3501 Measurement Results

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### Introduction

This report summarizes measurement results obtained from the AP3501E sampler. The sampler was connected to the measurement setup by several SMA coax cables. Two cables of equal length were attached to the LO ports, a short cable was attached between RF input and signal source (RF or DC). The IF output was monitored via a sampling oscilloscope and spectrum analyzer, respectively.

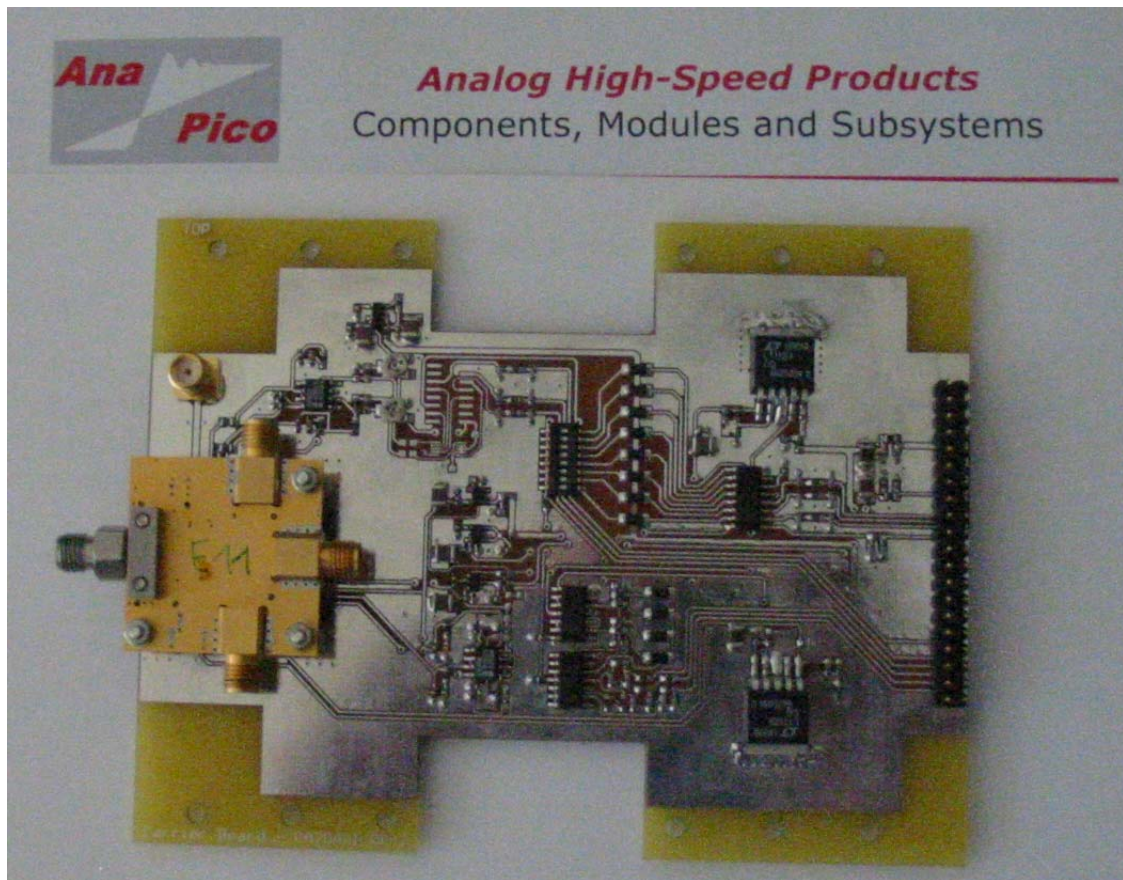
All measurements were performed at room temperature, with the default bias conditions, using different sampling rates (for time domain measurements typically 10 MS/s; for frequency domain measurements typically 500 MS/s, unless otherwise stated). The LO was supplied by a HP71603B pulse pattern generator (50% duty cycle, with an amplitude of 1.0 V<sub>pp</sub> differential and approx. 100 ps rise and fall times). The equipment used for testing is listed in Table 1. The RF signal sources were phase locked to a common 10 MHz reference.

The following voltages were used throughout all measurements:

Voltage	Default	Remarks
Vcc5	5.0V	150mA current
Vcc2	6.0V	230mA current
Vcc3	2.5V	
Vee3	-3.0V	
LO	1.0Vpp	Differential operation recommended, but single-ended operation possible
Vbias+	0.8V	
Vbias-	-1.4V	
Vopamp+	+5V	
Vopamp-	-5V	

Table 1: Equipment used for evaluation of the sampler

Type	Model	used for
40 GHz synthesizer	R&S SMP 04	Bandwidth, Harmonic, Intermod. Meas.
20 GHz synthesizer	HP 8341A	Intermod. Meas.
Pulse pattern generator	HP 71603B	LO source
Sampling oscilloscope	HP 83480A with HP 83484A 50 GHz plugin	DC response, DC linearity
Spectrum Analyzer	Advantest R3465M	Bandwidth, Harmonic, Intermod. Meas.
Oscilloscope	TEK 2465BCT	
Power meter	HP 437B with HP 8487A 50 GHz sensor	Calibration
Prog. DC source	HP 6632A	DC response, DC linearity
DC power supplies	Agilent E3610A, E3611A, E3630A	



Photograph of the AP3501 sampler prototype mounted bottom-side up on an evaluation board.

## DC linearity

The DC linearity of the sampler was measured by sweeping a DC voltage at the sampler input from  $-1.5\text{V}$  to  $+1.5\text{V}$  and obtaining the sampled IF voltage (Fig. 1). The conversion gain is 0.8 (approx.  $-2.5\text{ dB}$ ), varying approx.  $\pm 1.5\%$  over a  $\pm 1\text{V}$  input and below  $\pm 0.5\%$  for the  $\pm 0.5\text{V}$  range (Fig. 2). The measurements were made with  $10\text{MS/s}$  sampling rate and "reset operation" to guarantee memory-free sample by sample operation. The measurement ripple is caused by noise on the DC input voltage.

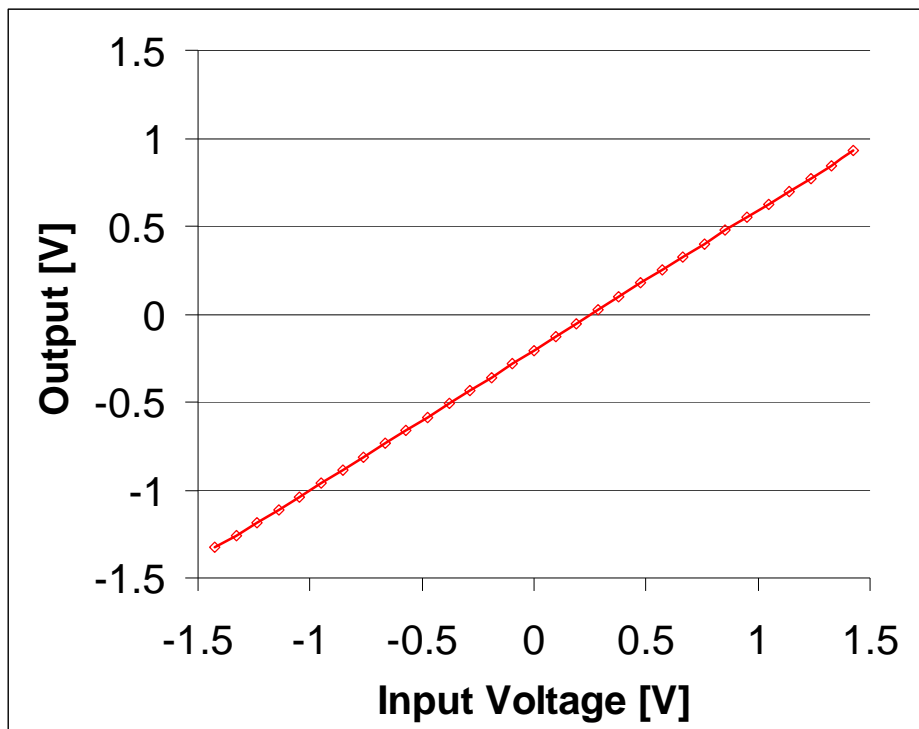


Figure 1 Measured DC response of the AP3501 sampler.

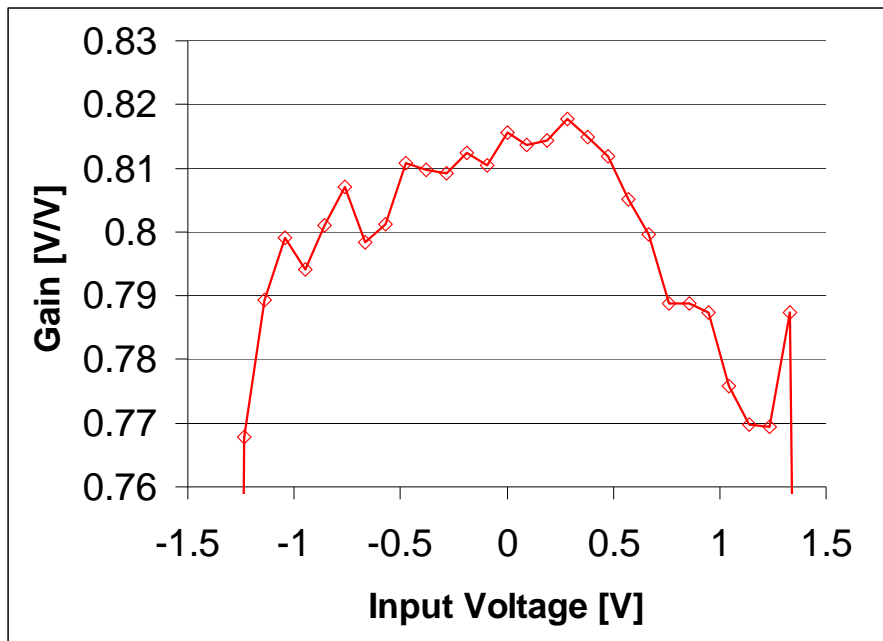


Figure 2 Measured DC linearity of the AP3501 sampler.

The sampling rate dependence of the conversion efficiency was measured as shown in Fig. 3. A single-ended LO with 300 mV amplitude was used for this measurement. The conversion efficiency remains almost unchanged when increasing the sampling rate from 1 MS/s to 20 MS/s. At 40 MS/s, the efficiency starts to increase due to non-ideal reset operation. The situation can be dramatically improved by lowering the amplitude of the reset signal.

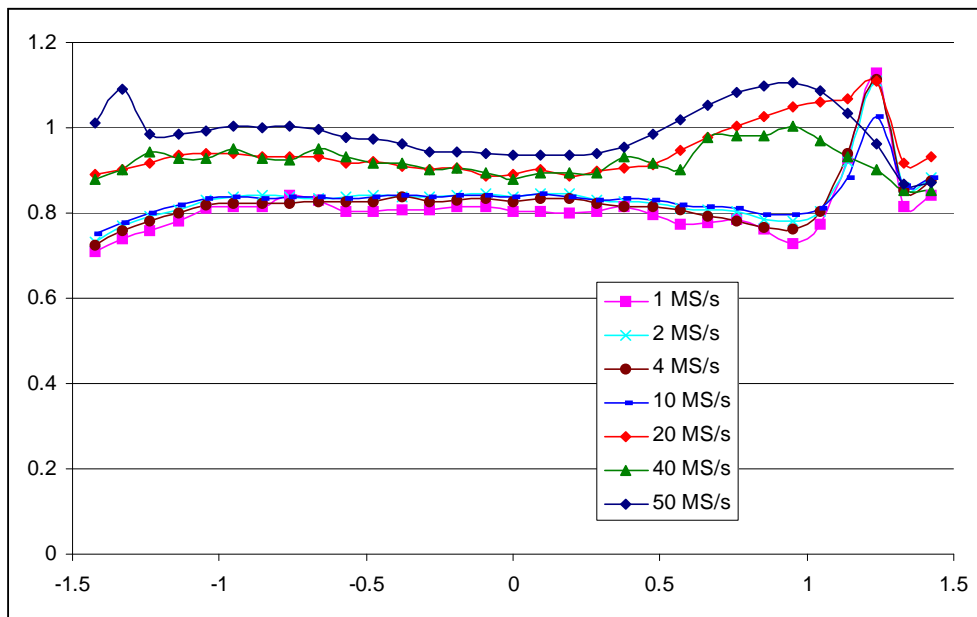


Figure 3 Sampling efficiency vs. sampling rate.

If the sampler is operated in the sample-and-hold mode, then the IF output will be reset after every sampling instant. The resulting IF waveform is a rectangular pulse with a height proportional to the sampled instantaneous RF voltage. The resulting IF signal waveforms (sweeping the input voltage from  $-1.5\text{ V}$  to  $+1.5\text{ V}$  in  $100\text{ mV}$  steps) are shown for  $1\text{ MS/s}$  (Fig. 4) and  $10\text{ MS/s}$  (Fig. 5). The pulse has a selectable duration of 20 to 80 % of the sampling time interval. With a 50% duty cycle, an operation of at least  $65\text{ MS/s}$  with memory-free samples is possible.

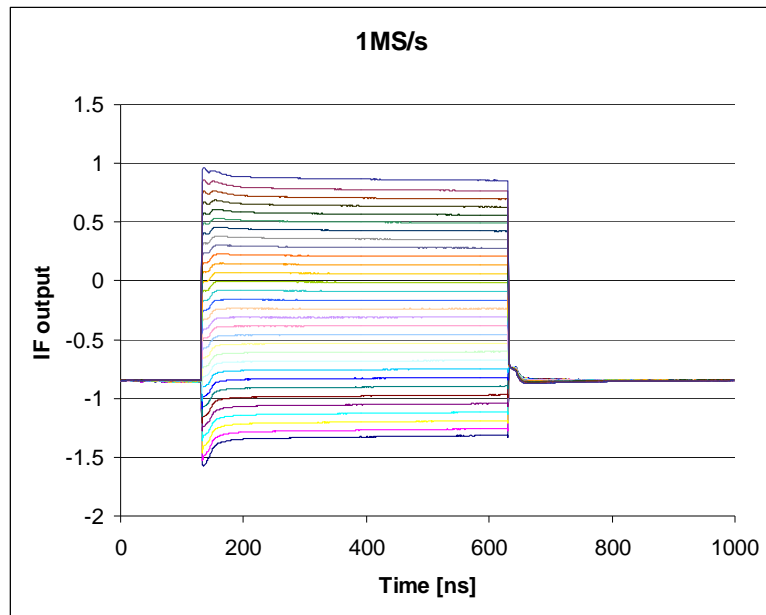


Figure 4 Measured DC response of the sampler (operated in sample-hold-reset mode). The DC voltage at the input was stepped from  $-1.5$  to  $1.5$  V in  $100$  mV steps, the sampling rate  $10$ MS/s.

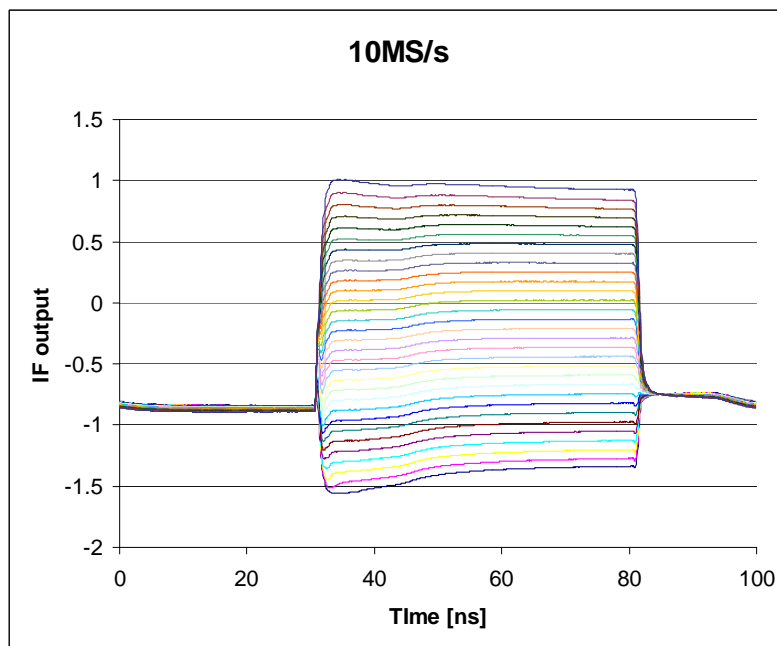


Figure 5 Measured DC response with sampling rate of  $10$  MS/s.

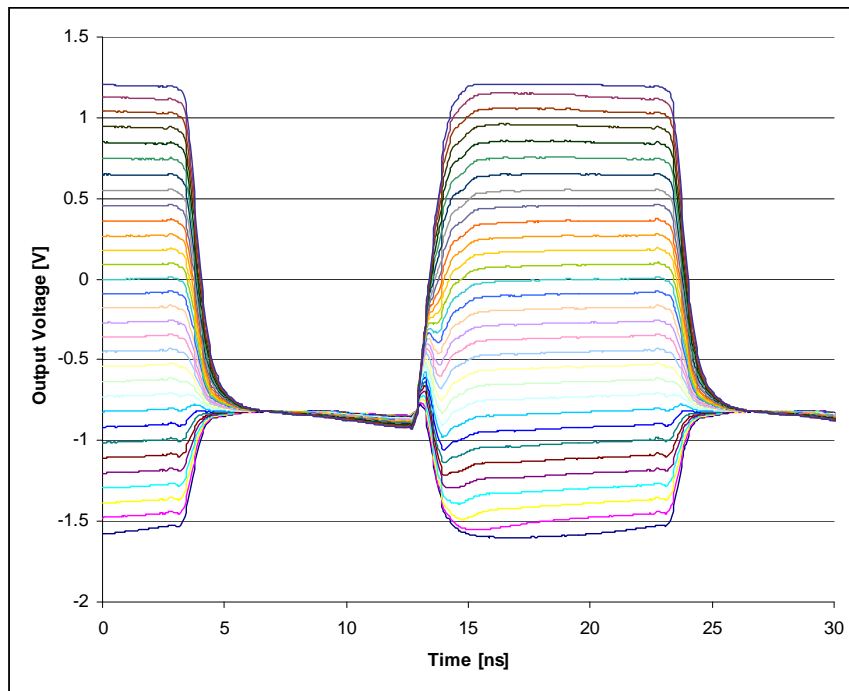


Figure 6 Measured DC response with sampling rate of 50 MS/s.

## RF bandwidth

The RF bandwidth of the sampler was measured as shown in Fig. 7. The RF frequency was swept from 1 GHz+2 MHz to 36 GHz+2 MHz in 1 GHz steps and the down-sampled IF signal power was recorded. A sampling rate of 500 MS/s was used. The resulting frequency characteristic indicates a bandwidth of approx. 34 GHz. This measurement was performed in a test fixture with a SMA connector at the RF input. The ripple around 26 GHz can be explained with a resonance of the SMA connector. The final product will use a K-connector at the RF input and is not expected to show that large ripple.

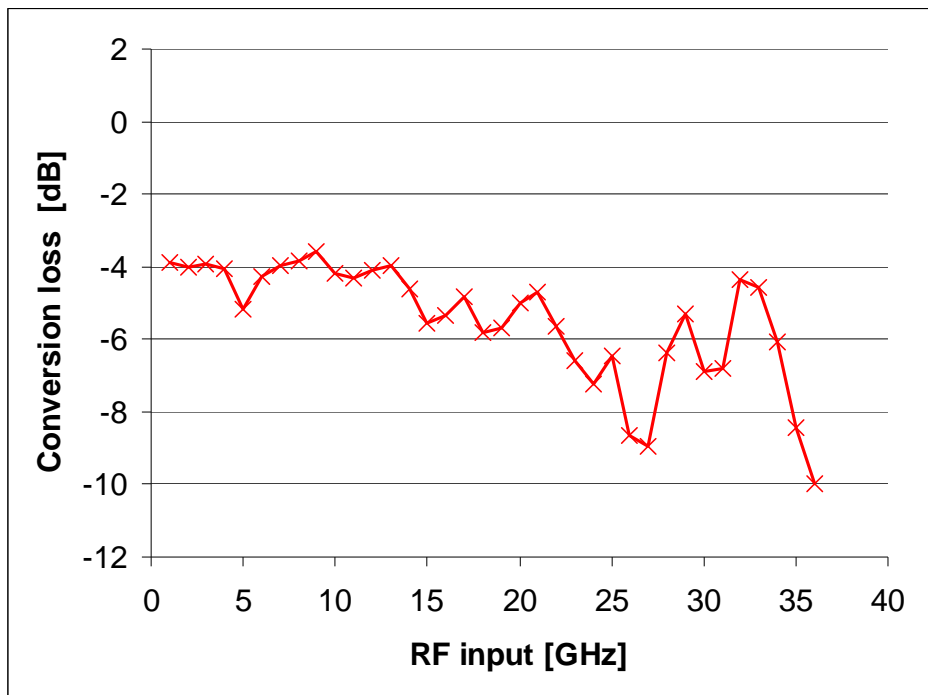


Figure 7 Measured RF bandwidth.

## Distortion performance

The harmonic distortion of the sampler was measured by sweeping the RF input power of a 5.002 GHz carrier and monitoring the power of the down-sampled IF and its harmonics (Fig. 8). The sampling rate in this case was 500 MS/s. A spurious-free dynamic range (SFDR) of more than 60 dB is measured for a -5 dBm input power, corresponding to a high third order intercept point of +27 dBm.

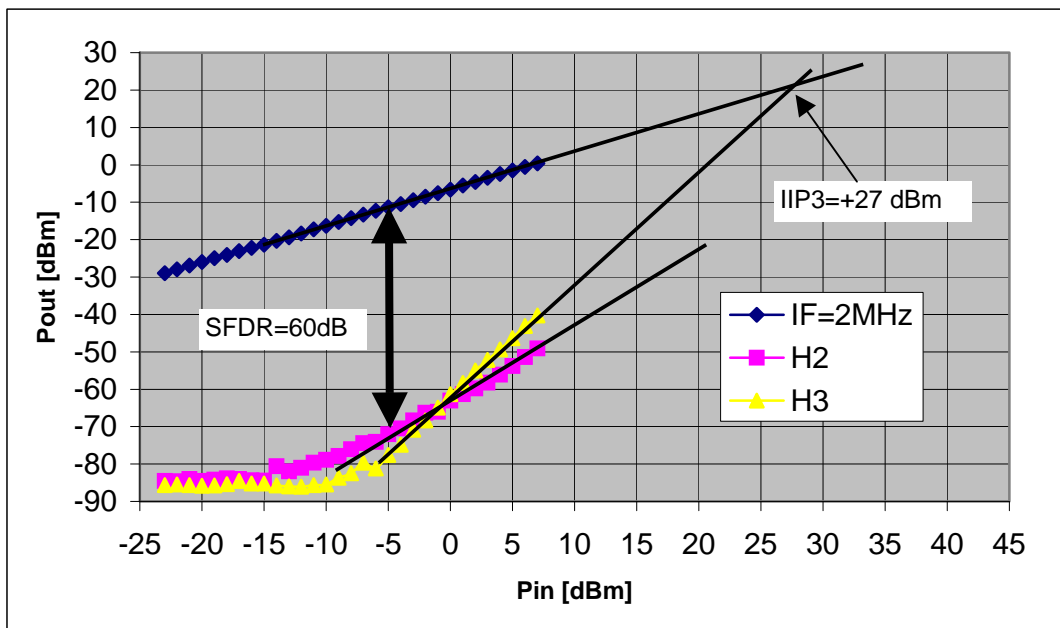


Figure 8 Measured harmonic distortion of the AP3501 ( $f_{RF} = 5.002 \text{ GHz}$ ).

The harmonic distortion performance versus IF frequency was measured in Fig. 9. The RF frequency was swept from 5.001 to 5.060 GHz and the IF spectrum was monitored. The sampling rate in this case was 500 MS/s, the RF input power was  $-5 \text{ dBm}$ . The harmonic distortion is almost independent of IF frequency. The cause of the IF roll-off is currently investigated.

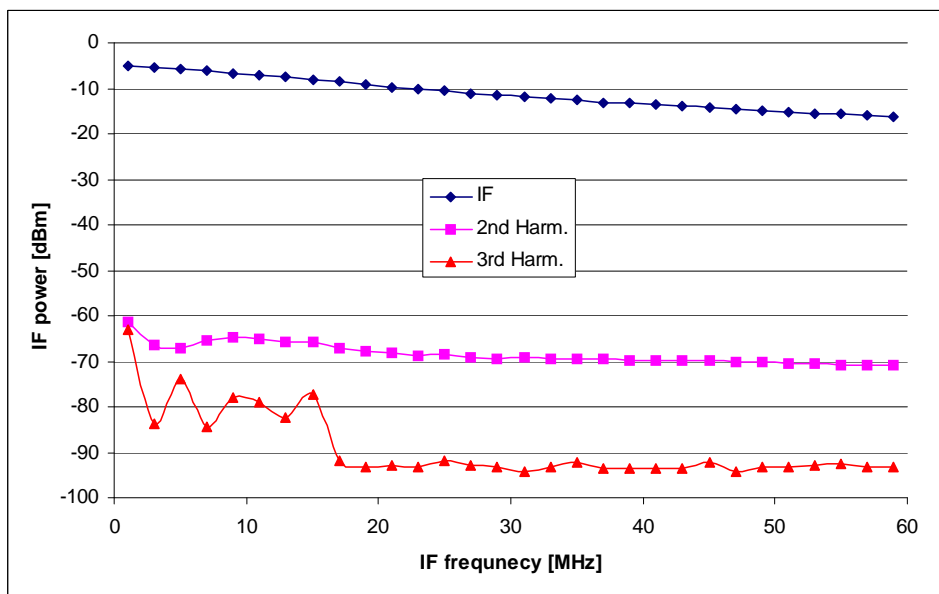


Figure 9 Measured harmonic distortion as a function of IF frequency ( $f_{RF} = 5 \text{ GHz} + f_{IF}$ ). The sampling rate was 500 MS/s.

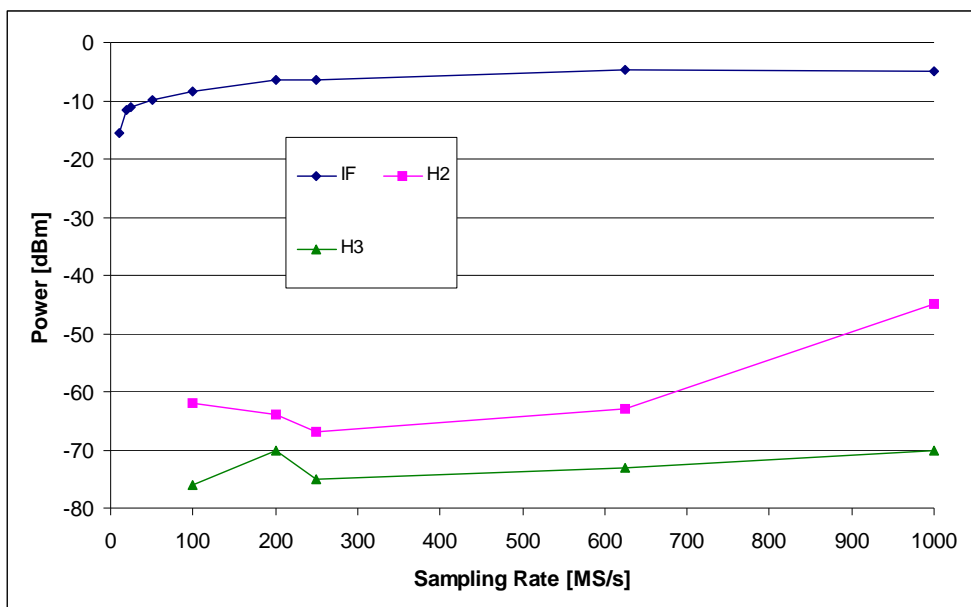


Figure 10 Harmonic distortion for different sampling rates /RF input power = -5 dBm).

The sampling rate dependence of the harmonic distortion was also investigated, as shown in Fig. 10. Harmonic distortion is only slightly dependent on sampling rate. However, at high sampling rates above 600MS/s the second harmonic is starting to degrade.

The intermodulation performance was also measured. Two 5 GHz tones with 100 kHz spacing and  $-5$  dBm power per tone are down-sampled with the AP3501 at 500 MS/s. The resulting spectrum is shown in Fig 11. The third order intermodulation product is 63 dB down from the fundamental tones, corresponding to an IIP3 of  $+26.5$  dBm. This is in good agreement with the IIP3 extracted from the harmonic distortion measurements.

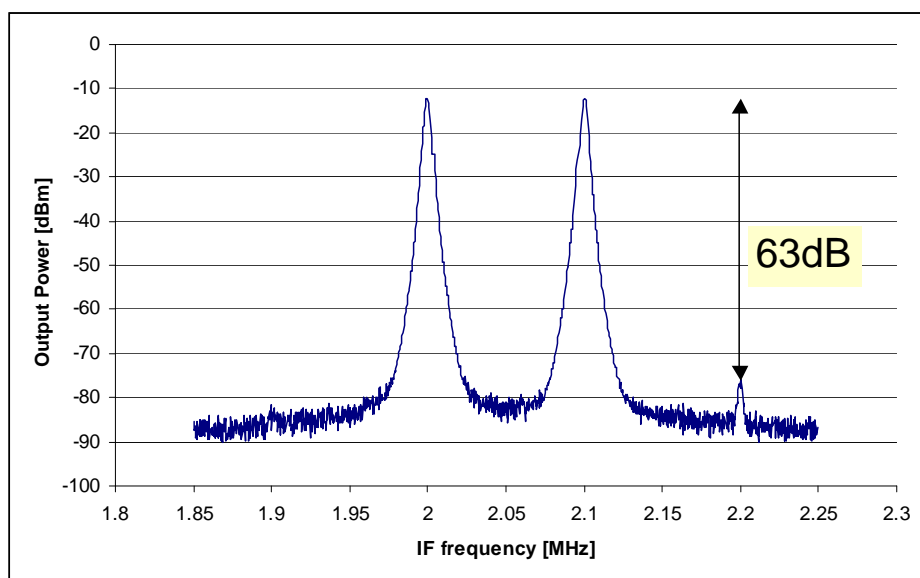
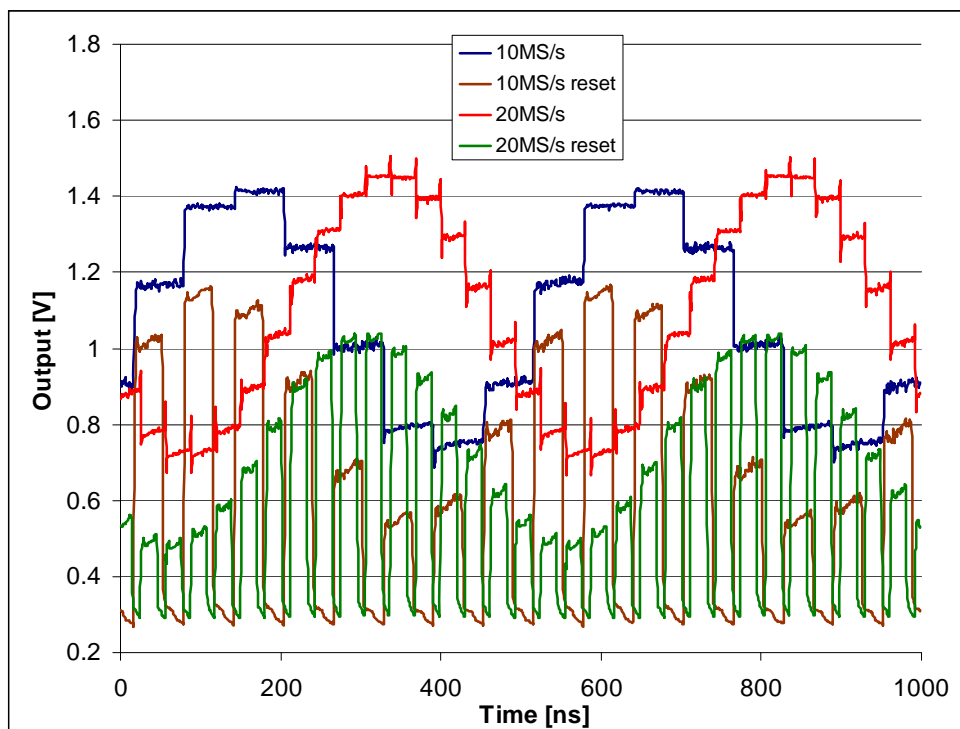


Figure 11 Intermodulation distortion spectrum ( $f_{RF}=5.002$  GHz and  $5.0021$  GHz, power is  $-5$  dBm per tone; RBW=10 kHz, VBW=1 kHz)

## Sample-hold-reset operation

The sampler was tested for proper operation of the reset function as shown in Fig. 12. Two traces are shown: in blue the down-sampled IF without reset active, in pink the same IF signal and the reset active. From that measurement it can be concluded that

- the intrinsic sampling efficiency is close to unity,
- the reset operates properly and does not affect the sampling efficiency.



*Figure 12 Down-sampled output waveform over time ( $f_{RF}=6.408$  GHz,  $f_{LO}=64$  MS/s,  $f_{IF}=8$  MHz). In blue, the waveform without reset, in pink with reset applied.*

## RF to LO isolation (Blow-by)

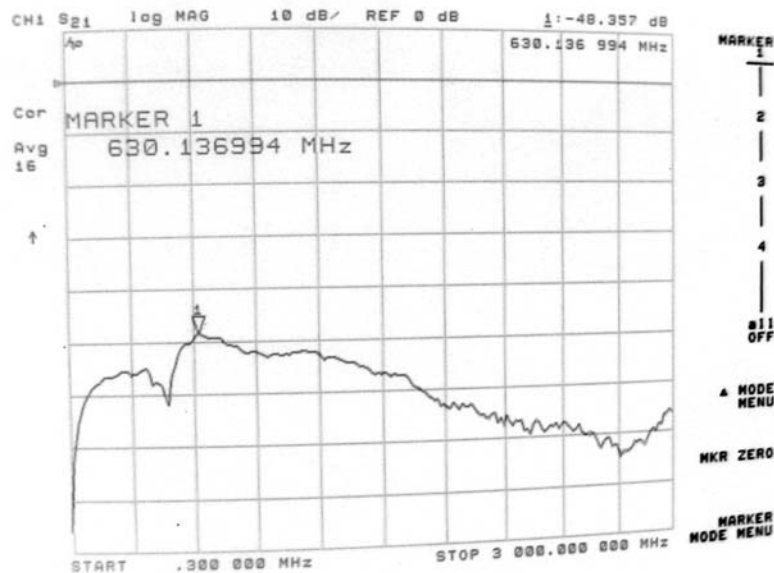


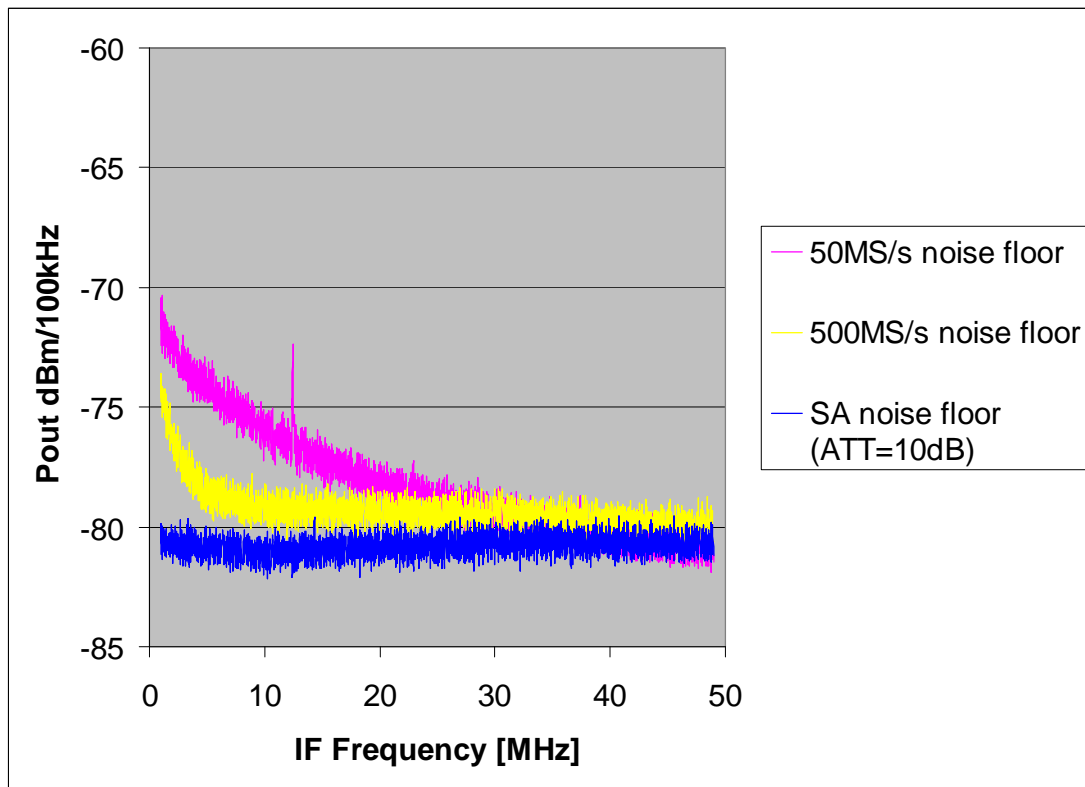
Figure 13 Measured RF-to-IF isolation (blow-by) of the AP3501

An important figure for applications in sampling oscilloscopes is the RF-to-IF isolation, which can cause uncorrectable signal distortion like baseline wander in sampled digital bit patterns. Fig. 13 shows the measured performance from 300 kHz to 3 GHz. The isolation is better than 48 dB over the entire frequency range.

## Noise performance

In order to determine the sensitivity level of the sampler module, the output noise spectrum was measured using a spectrum analyzer as a function of sampling rate to determine the output RMS noise voltage. Fig. 13 shows the noise spectrum up to 50 MHz for two different sampling rates. Note that the  $-80$  dBm correspond to the noise floor of the spectrum analyzer.

The noise spectrum shows a  $1/f$  component at lower frequencies. That  $1/f$  component is caused by the flicker noise from the internal IF amplifier. Integrating the noise power density obtained at 50MS/s



over 50 MHz yields a RMS output noise voltage of  $470 \mu\text{V}_{\text{RMS}}$ .

Figure 14 Measured output noise spectrum at different sampling rates. The RBW is 100 kHz

## Jitter performance

To determine the aperture jitter, first the sampler output was measured at zero DC voltage input. This gives a RMS noise voltage  $v_1$  at the output. Second, a slightly delayed version of the LO signal (with a known amplitude and rise time) was applied to the RF input of the sampler such that the LO was sampling itself. The delay was adjusted such that the sampling position was right at the zero crossing of the input signal. The measured RMS noise voltage  $v_2$  is a sum of the equipment and sampler noise  $v_1$  and the noise voltage  $v$  that is caused by the uncertainty of the sampling event. To determine the jitter the noise voltage  $v$  is divided by the known slow-rate SR:

$$\text{jitter} = v/\text{SR} = \sqrt{(v_2^2 - v_1^2)}/\text{SR}$$

The measurement was performed at 10 and 20MS/s and a slew-rate of 2V/100ps. The calculated jitter was 65 and 55 fs, respectively. For this measurement, the LO was supplied single-ended. A slightly better jitter can be expected with a differential LO signal.

## Conclusions

In this report the most important performance parameters of the AP3501 were characterized. The AP3501 shows performance close or within specification. Table 2 summarizes the measured versus specified key performance parameters.

Table 2: Summary of specified versus measured key performance parameters

Parameter	Spec Typ.	Spec Max.	Measured	Units	Note
input bandwidth	35		34	GHz	With SMA
Sampling rate		50/400	64/600	MHz	
Spurious free dynamic range	60 at -10dBm		63 at -5dBm	dB	1
IF bandwidth	200		tbd	MHz	
Linearity	±1%		±1.5%		
Output offset		100	tbd	mV	2
Aperture jitter		0.5	<0.1	ps <sub>RMS</sub>	
Output noise		0.5	0.47	mV <sub>RMS</sub>	3
RF Input impedance	50		52	Ohm	At DC
Input reflection coefficient		0.1	tbd		
Strobe input impedance			96 differential	Ohm	
Strobe input amplitude	1.0		0.25 to 1.5	V <sub>pp</sub>	4
Conversion efficiency	1		0.8/1.6	V/V	5
Latency	6		6.5	ns	
Power dissipation	2		2.18	W	

Notes:

1. measurement at 5GHz and 500MS/s with -5dBm input signal.
2. can be adjusted externally
3. Integrated over the 50MHz (sampling rate = 50MS/s)
4. differential. single-ended operation is possible with V<sub>pp</sub><1V
5. with a 50 Ohms output impedance. With a low impedance output configuration, the conversion gain is 1.6

## Document History

Version/Status	Date	Author		Notes
V10	2006-8-22	jk		preliminary release
V11	2006-9-10	jk		Added jitter measurements
V12	2007-04-16	ul		editorial update