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Demonstration of 10^{-22} W Signal Detection Methods in the Microwave Range at Ambient Temperature.

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Abstract

The detection of a very faint signal in a noisy environment is of considerable interest in different applications including antihydrogen spectroscopy and also microwave axion and 'hidden photon' detection. We demonstrate with a very simple setup using a commercial signal generator and an FFT signal analyzer the detection of a microwave signal of 10-22 W at ambient temperature.

Geneva, Switzerland
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1. Introduction

We consider a narrowband single frequency signal added to a thermal noise background. The available noise power from an ohmic resistor is given by the well known relation

$$p_N = k \cdot T$$

where p_N is the noise power density, k the Boltzmann constant and T the absolute temperature. At room temperature (300 K) this amounts to −174 dBm/Hz or $4 \cdot 10^{-21}$ W/Hz.
Provided that the signal power is nearly an infinitely narrow line (Dirac delta function like spectral distribution) we can theoretically enhance the detection threshold level to impressive values by simply reducing the resolution bandwidth of the vector signal analyzer (VSA).

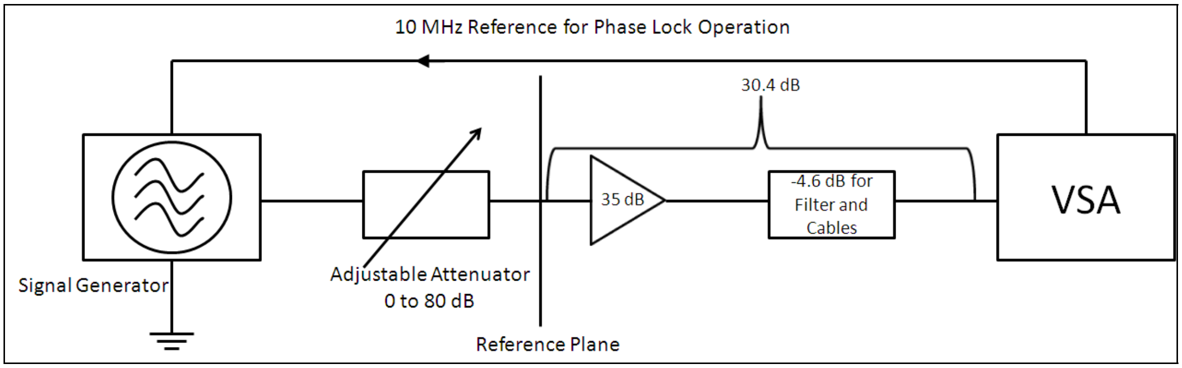

Figure 1: Schematic diagram of the test setup

2. Description of the Measurement Setup

The measurement setup is very simple and depicted in Figure 1. We use a commercial signal generator, type Rohde und Schwarz SM300 9KHz-3GHz, which can be set to a minimum output power of −120 dBm by the internal attenuator, and, in order to further reduce the signal strength, an adjustable external attenuator of up to 80 dB. If we would consider a 1 Hz observation or resolution bandwidth, a signal of −180 dBm (one of the test signals) would already be 6 dB below the thermal noise power density of −174 dBm. In order to display this signal on a VSA we use a low noise amplifier, with a gain of about 35 dB at the operating frequency of 2.5 GHz and a noise figure of 2 dB. For the amplifier a MITEQ AFD3-0824 was used, which is a more than 20 year old amplifier and not longer listed in catalogues and on the web (data in appendix). The VSA used was an Agilent MXA N9020A 20Hz-3.6GHz, with running a VSA89600 application on it. The afore-mentioned VSA89600 application makes use of the basic functions of the MXA N9020A and offers the FFT functionality.
After the amplification, a narrowband filter with 10 MHz bandwidth is used, to avoid getting too much integrated signal power from the wideband amplifier – amplified thermal noise – which would lead to saturation of the input stage of the VSA. The VSA can be set to very narrow values of the resolution bandwidth (RBW) by means of an internal Fourier transform algorithm. The RBW setting in the instrument is the same as the Noise Equivalent Bandwidth. In the present case the minimal practicable useable RBW is 3 mHz. It turned out that this instrument could not perform measurement tasks longer than 2 h, for this parameter settings for unknown reasons. A RBW of 3 mHz corresponds to an equivalent time trace acquisition duration of about 8 minutes (for single trace with Hanning window, which has very small side lobes), with a span of 5 Hz and 6401 points. If averaging of 10 is applied, the measurements time is also increased by 10 (to 80 min for these settings) .The applied video averaging is indicated by the RMS symbol in the top center of all measured traces, the number gives the number of averages. The resolution bandwidth and furthermore the measurement time, depends of the number of points and the span observed. We could also use a 50 Hz Span and 64001 points leading to the same measurement time of 8 minutes and the same resolution, the only difference is the larger frequency span, which may contain information of nearby signals. The measurement time is influenced by the RBW only — the smaller the RBW gets, the longer the measurement time becomes.

The hardware transfer function (Figure 2), of the single transmission chain including low noise amplifier, filter and cables was measured as 30.4 dB (effective gain) for the test frequency of 2.5 GHz (determined by the characteristic of the narrowband filter).

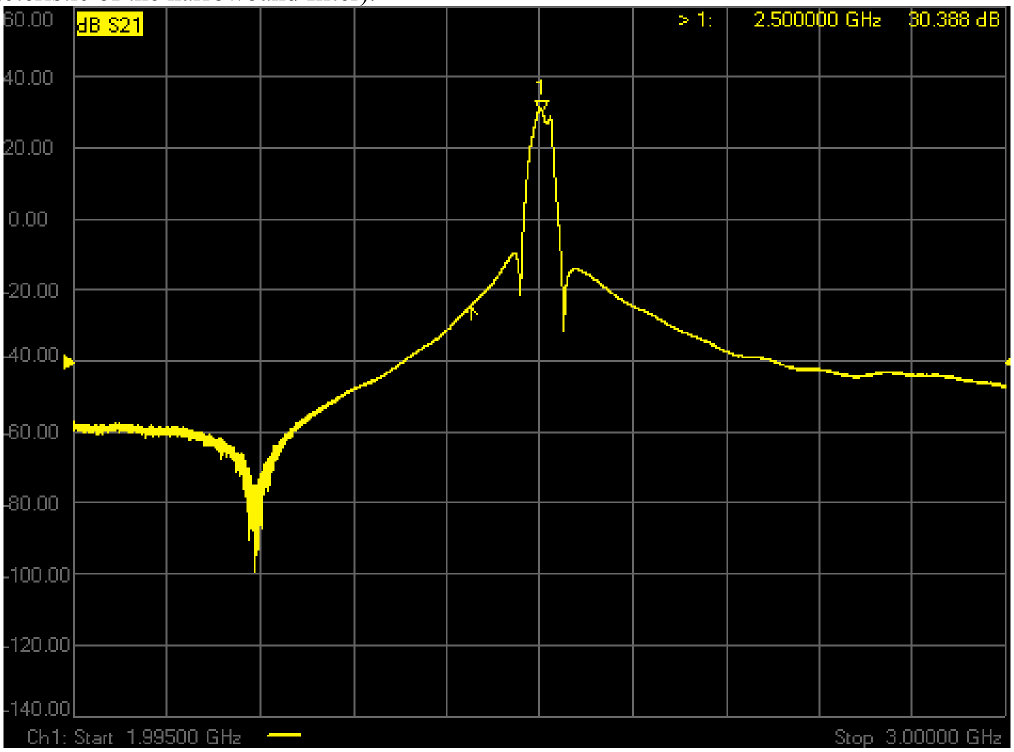

Figure 2: Result of the S_{21} measurement of the test setup (amplifier, filter and cables – no attenuator) to determine the effective gain at the test frequency of 2.5 GHz.

It is absolutely vital for this type of measurement to use a phase lock of the 10 MHz reference (rear output and input) between the signal generator and the VSA. Otherwise the slow frequency drift between the two quartz reference oscillators would not ensure the tracking of both instruments within 30 mHz during the measurement time of 1 minute (with 10 traces averaged 10 minutes).

This phase/frequency lock technique however does NOT stabilize the actual frequency to the order of mHz or less, but it assures tracking within mHz or less. The typical frequency drift of microwave synthesizers over an hour can easily be in the order of several Hz, depending on the quality of the internal quartz time base. Tests have shown that the relative drift between the two used instruments can amount to several Hz if they are not synchronized. In Figure 3 the results of a measurement of a −150 dBm signal at the reference plane can be seen, it has to be considered that in this case both clocks were synchronized. The measured value is in agreement with the theoretical computed one to within 0.4 dBm. Figure 4 shows the same measurement without both clocks being synchronized, the result is that through the drift of both clocks the signal energy is split into different frequency bands and the peak gets smaller and smears out. It also has to be noted that both clocks differ at about 750 Hz. The overall measured power in both cases is the same, with the difference that the power is distributed over several frequency bands (resolution bandwidth) in the second case, which makes the detection of a jittering signal (clock) at even smaller signal levels practically impossible. Also, this measurement gives a good estimate of the relative frequency drift between the signal generator and the VSA, when they are not in phase lock. The difference between these two measurements shows very well the importance of a synchronized measurement, or a very stable reference. Only in this case, as the measured signal was generated by a signal generator, it was possible to synchronize both clocks. For other measurements, without the possibility to synchronize the VSA to the signal, a very stable reference is required and when going to such low signal levels the frequency of the measured signal has to have a very stable frequency.

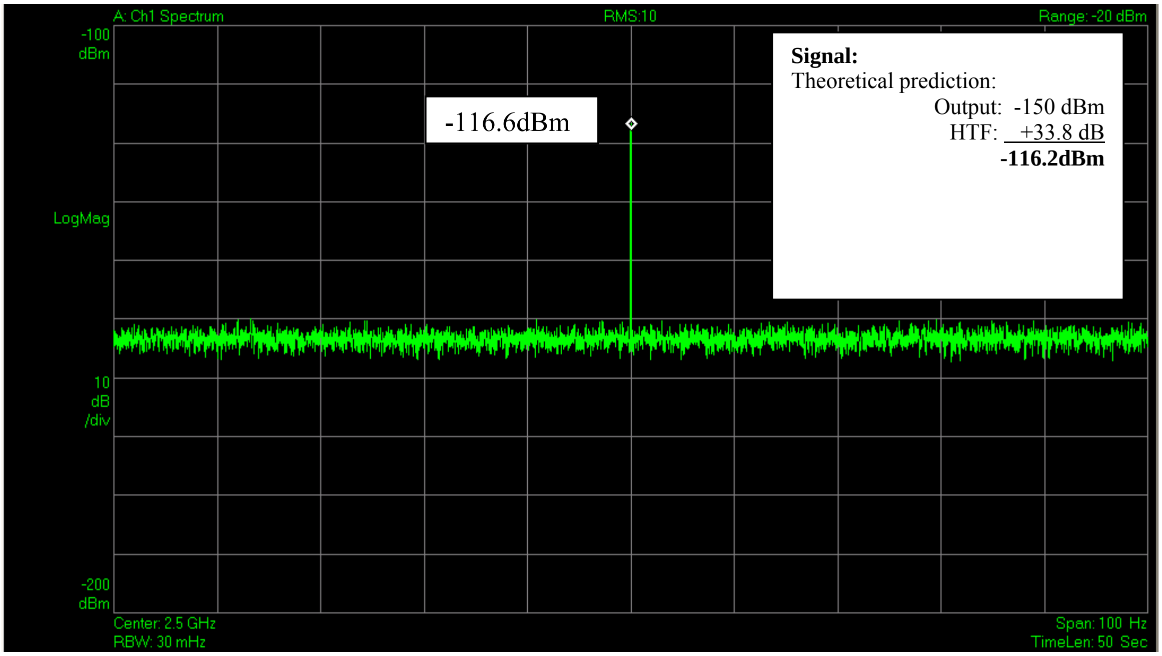

Figure 3: −150 dBm signal, signal generator and VSA synchronized

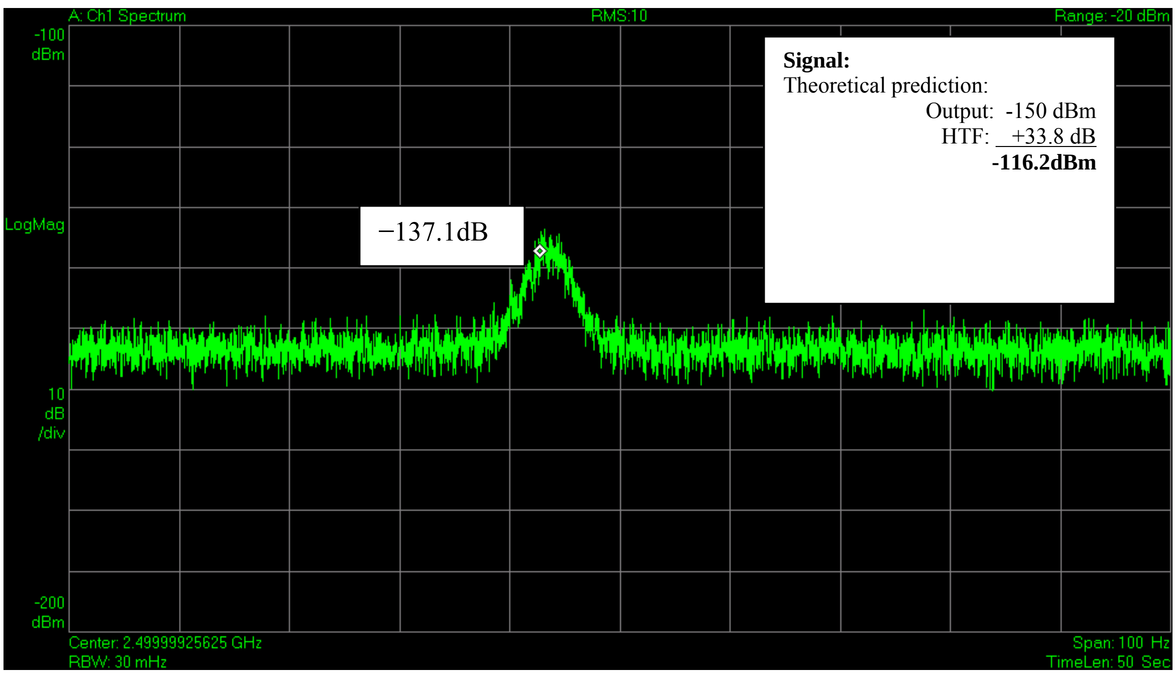

Figure 4: −150dBm signal, signal generator and VSA not synchronized

3. Meaning and Interpretation of noise traces from a Signal Analyzer

It should be made clear that the traces (of noise signals) shown on the spectrum analyzer display have undergone a considerable amount of signal treatment. In Figure 5 the block diagram of a classic superheterodyne spectrum analyzer can be seen. The signal is first attenuated and pre-filtered at the input, then down-converted by the mixer. After the mixer the signal is set to the appropriate level for the correct handling in the subsequent signal treatment chain and filtered at the desired frequency. The signal then contains only frequency components determined by the IF-filter bandwidth. After the filtering the signal is amplified and the modulus is taken by a logarithmic amplifier to provide the display in logarithmic vertical scale. Before displaying, the signal passes the envelope detector, which usually detects the peak, and is finally low pass (video) filtered. The (noise) signal, which is present before the envelope detector, contains all frequency components that pass the band pass IF-filter. These (noise) signals superimpose and their peak value is then detected by the envelope detector. For noise, these signals are stochastic and give varying amplitude around an average value (real noise). To get this real value and to smooth the trace, averaging of the video traces is required. This reduces the variance of the noise floor around its mean value and makes a signal slightly above the noise floor distinguishable.

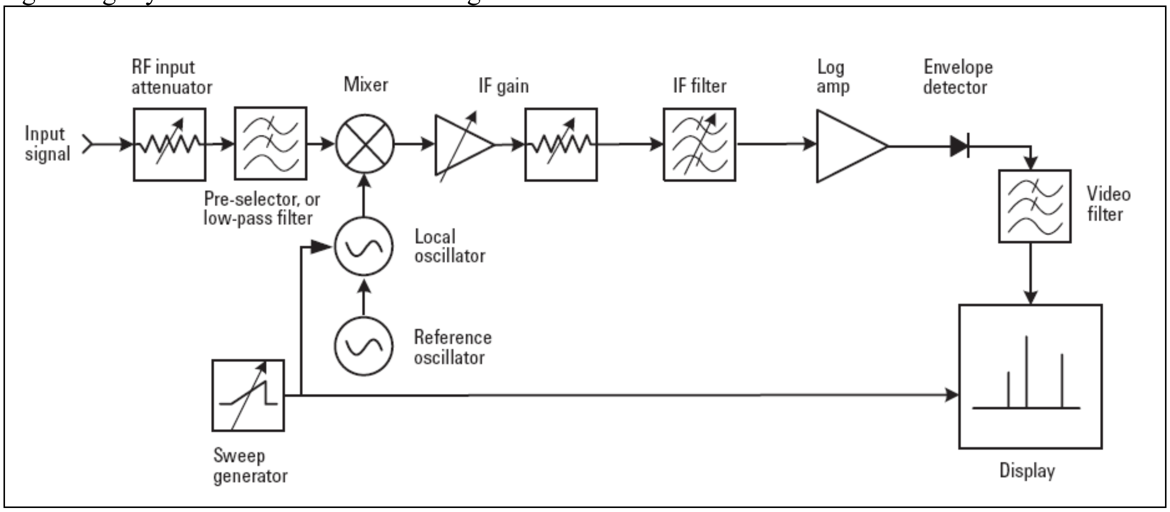

Figure 5: Block diagram of a classic superheterodyne spectrum analyzer [1]

4. Results

Figure 6 shows a measurement with 10 averagings of the spectral trace but with the output power of the signal generator set to −110 dBm and an external attenuation of 60 dB. In this case, the thermal noise at 3 mHz is −199 dBm while the signal level is −170 dBm. This leads to a theoretical signal to noise ratio of 29 dB. Since the measured ratio is about 27 dB, we find a good agreement of theoretical prediction and measurement. As the signal to noise ratio is high enough in this case, no subtraction of the noise power is necessary.

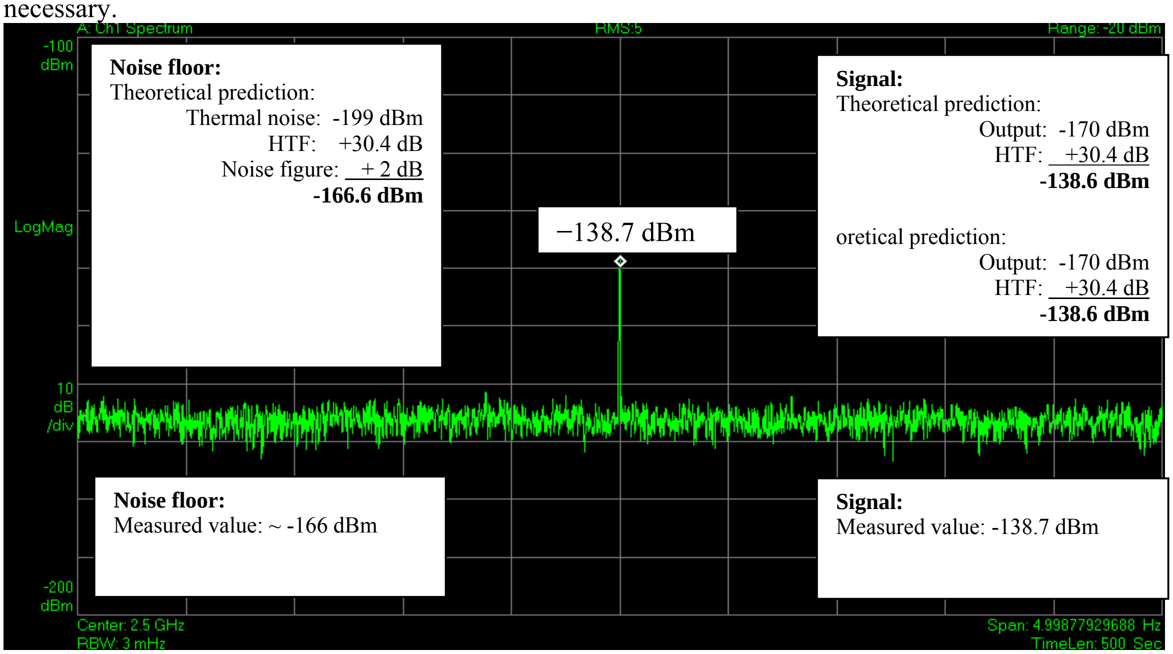

Figure 6: Measurement result –17 dBm signal@reference plane, 3 mHz resolution bandwidth

Figure 7 again shows a measurement result with 10 averagings of the spectral trace. The output power of the signal generator was set to −120 dB via the internal attenuator and the external attenuator provided an additional attenuation of 60 dB. A simple theoretical calculation shows us that for a resolution bandwidth of 30 mHz we should expect a thermal noise power density at the input of the low noise amplifier of −189 dBm. This relates simply to the −174 dBm thermal noise power at 1 Hz reduced by 15 dB due to the operational resolution bandwidth of 30 mHz. Furthermore we have to add, for the signal to noise ratio, the 2 dB noise figure of the front-end amplifier. This leads to a calculated signal to noise ratio of 7dBm at the reference plane. It should be noted that the noise figure of the amplifier has to be subtracted. As can clearly be seen in Figure 7, the measured signal peak is about 5 dB higher than the nearby thermal noise, which is in good agreement with theory. It should be noted that the measured signal is 0.3 dB larger than the theoretically predicted one; this is due to the fact that the noise power is added to the signal power; for large signal to noise ratios this is negligible, but when measuring close to the noise floor, this starts to become relevant. A simple correction of the signal by subtracting the noise power gives us a corrected value of ~−150.3 dBm. (Note that the subtraction has to be done in linear scale)

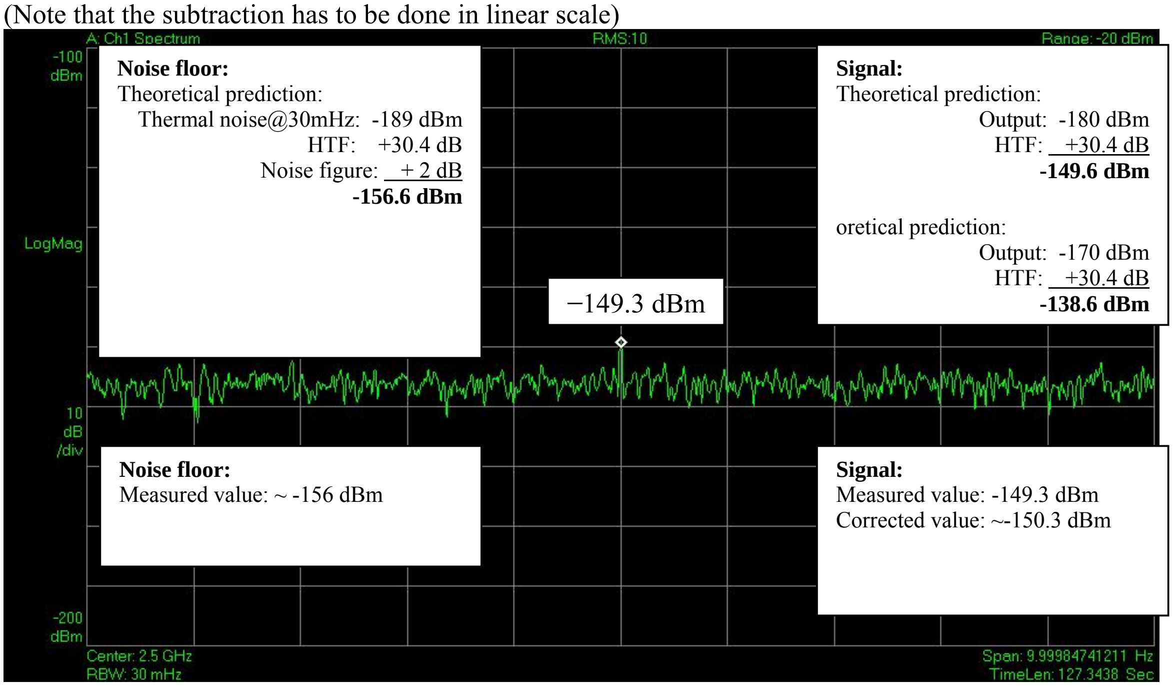

Figure 7: Measurement result −180 dBm signal@reference plane, 30 mHz resolution bandwidth

Now, as a cross check, we had to make sure that we were not fooled by the RF leakage of the cables, instruments and connectors. As a check, we first disconnected and terminated the output of the external attenuator and the input of the front end of the amplifier without connection between both and no signal was seen at all (Figure 8).

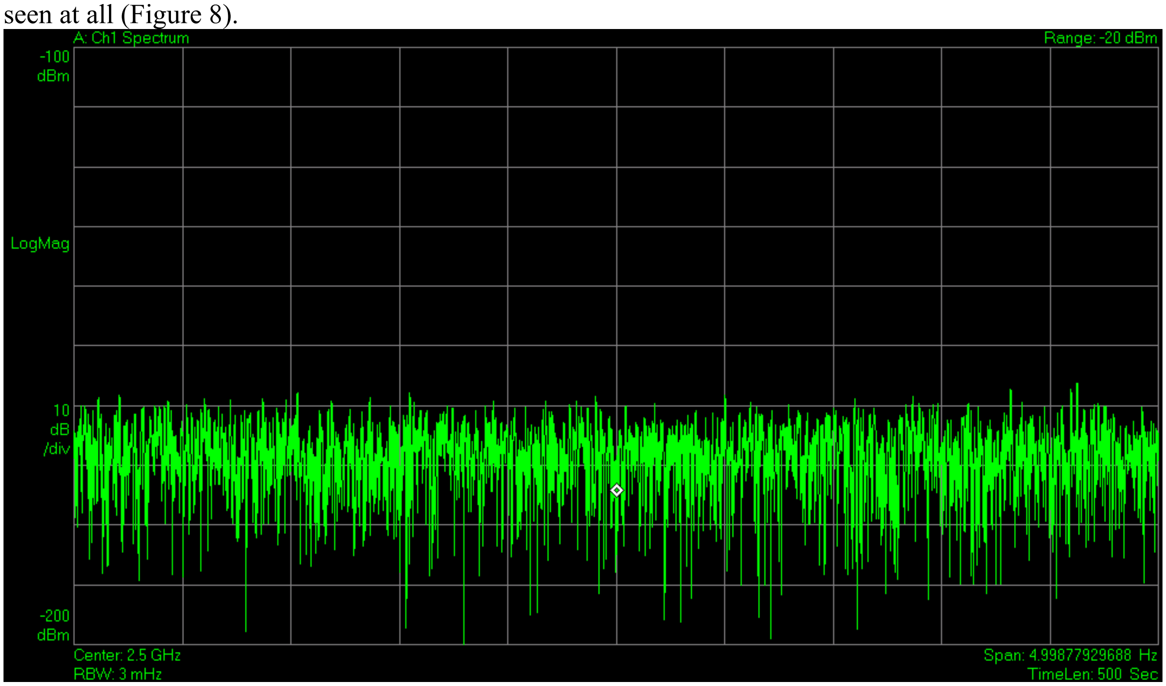

Figure 8: Test with disconnected and terminated output of the external attenuator and the input of the front end amplifier. (no ground connection)

However as a final test under the same measurement conditions having a terminated cable from the attenuator chain in contact (outer conductor only) with the input of the front end amplifier resulted in a small visible signal. This indicates a small amount of RF leakage via cladding modes and leakage via RF connectors. This observation indicates the practical limits of this very simple measurement setup.
In order to minimize these cladding modes, EMC ferrites were used around the attenuator as well as the connectors of the amplifier (Figure 9). Since the filter picked up RF signals via cladding modes on the cables, we decided to omit it. Those cladding modes are probably excited in the vicinity of the generator via non-perfect connectors of the external attenuators. It is assumed that there is no risk of saturation of the input stage of the VSA, since we do not expect a significant amount of signal power in this test.

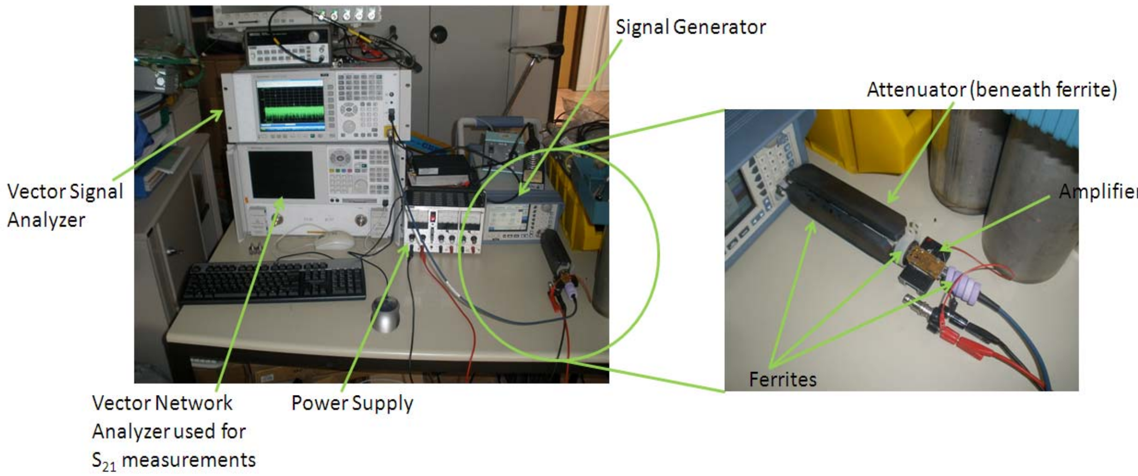

Figure 9: Test setup with EMC ferrites in order do attenuate cladding modes

Using the improved test setup depicted in Figure 9, a signal of −195 dBm should be present at the reference plane. However the signal is still higher due to a finite attenuation of the cladding modes by the ferrites. A HTF of the amplifier and the cables gave a gain of 33.8 dB in this case, due to the lower attenuation achieved by removing the filters. In Figure 10 the results of the measurement can be seen, note that the subtraction of the noise power reduces the signal by 0.9 dB, so it already has a considerable influence at this signal to noise ratio. The measured signal in this case is still by 4.8 dB too high, due to residual cladding modes. This leads to the conclusion that a signal with a power of roughly −190 dBm (10^{-22} W) is present and detectable at the reference plane. But even a signal 5 dB lower would be still clearly discernible on the same noise floor. Note the noise floor is shifted neither by connector and cable leakage nor by cladding modes.

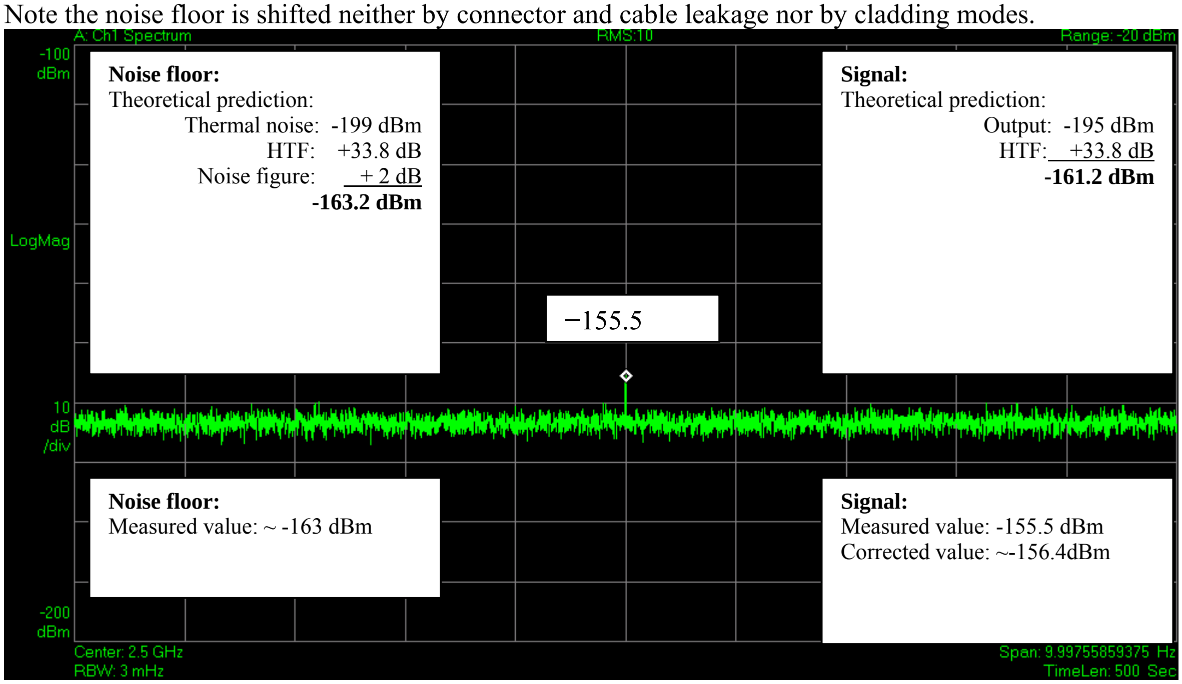

Figure 10: Measurement result -195dBm signal@reference plane, 3 mHz resolution bandwidth

5. Additional cross checks

To demonstrate the demand for the correction of the signal, when coming close to the noise floor, a measurement, where the spectral power density of the signal was equal to the spectral power density of the noise floor was performed. This results in a signal to noise ratio of 0 dB, and one would be tempted to believe that the signal is not visible. However, when taking into account that the spectral power densities of both signals are simply added in an uncorrelated manner, the sum signal will produce a peak of 3 dB (addition of uncorrelated signals), equivalent to twice the power. For this measurement sufficient averaging is required in order to reduce the variance of the noise floor and to be able to distinguish the actual signal. The resolution bandwidth for the measurement shown in Figure 11 is 10 Hz, which corresponds to a thermal noise power of −164 dBm. The noise is amplified by 33.8 dB and the noise figure of 2 dB of the amplifier has to be added. This results in a thermal noise power of -128 dBm to be present at the input of the VSA. To provide the same power level for the continuous wave (CW) signal, its intensity has to be set to −161.8 dBm at the reference plane, in order to finally get a displayed level of −128dB, which is equal to the thermal noise power. The measured peak of −125.05 dBm is roughly 3 dB higher than the surrounding noise floor and after correcting the value by simply subtracting the noise power from the signal power, the calculated value corresponds perfectly to theory. This example shows very well the need for this correction, when working close to the noise floor and also shows that a signal with a power density level equal to that of the noise floor is detectable, provided that sufficient averaging has been applied.

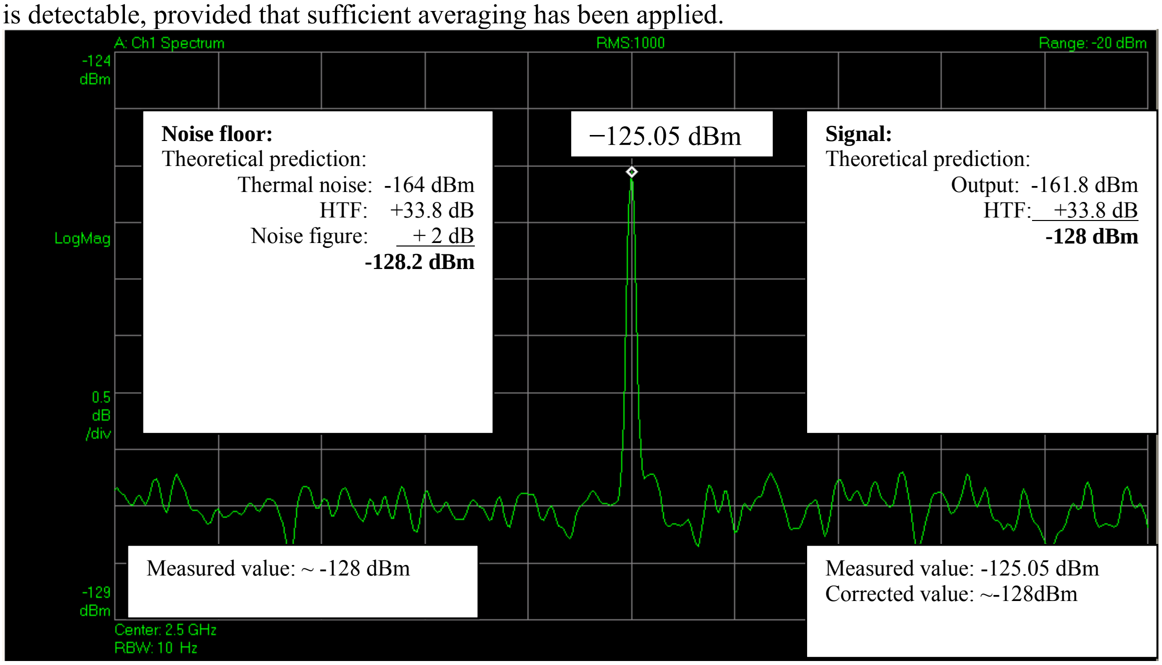

Figure 11: Equal noise and signal power density leading to a 3 dB peak in the display

6. Conclusions

It has been shown experimentally that even for very low signal levels in the order of down to 10^{-22} W the signal can be clearly seen above the thermal noise floor related to ambient temperature.
At 2.5 GHz this corresponds to a flux of 50 photons per second. Extrapolating this data for a signal source at cryogenic temperature (10 K) and corresponding low noise figure of the front end amplifier (0.1 dB) we can expect a further improvement of a factor 30. By further reducing the resolution bandwidth it might be possible to detect a microwave photon flux of less than one microwave photon per second for a very monochromatic (narrowband) photon source.
Furthermore for the same measurement parameters (500 seconds per trace for 3 mHz resolution bandwidth) it has also been clearly seen that the variance of the noise floor is strongly reduced by video trace averaging.

7. Outlook

In order to push sensitivity limits for this kind of measurements further we need to have a perfect control of the EMC/EMI shortcomings of the measurement setup which were already seen in the simple test setup

described above. Mitigation techniques include the ‘box in the box’ concept and signal as well as DC power transmission via optical fibers [2] to the preamplifier which is between the first and the second shielding.
This box in a box concept is nothing more than providing an additional shielding box (Faraday cage) around a first actual test unit.
A potential application may be the detection of antihydrogen atoms in a trap where we only have roughly 1000 antihydrogen atoms. In addition we expect a large amount of Schottky like noise from charged particles (antiprotons, positrons) which have not yet recombined to antihydrogen atoms. However, as the 21 cm line of the microwave hyperfine transition in (anti)hydrogen is very well defined, even a small number of photons (order of magnitude 10 per second) may be sufficient to measure the corresponding microwave signal with the technique described above. In this case it would be absolutely mandatory to stabilize the signal analyzer like receiver to an atomic clock either directly or via GPS, (phase/frequency lock mentioned above).
As for microwave axion and ‘hidden photon’ detection [3] this frequency lock concept which allows going down to very small effective resolution bandwidths (probably μHz or less) may lead to an increase of detection threshold by several orders of magnitude with respect to previously used or suggested concepts. However we have seen already in this study the potential (going down to about one milliHz resolution bandwidth) but also the limitations of conventional phase lock loop techniques using the 10 MHz reference. As we observed differential phase noise in the milliHz bandwidth region, it might be better for the application discussed in [3] to apply serrodyne methods to produce mixing and other auxiliary (calibration) frequency lines from some main reference in the GHz range.

8. References

[1] Agilent Spectrum Analysis Basics, Application Note 150, Agilent Technologies, July 14, 2004

[2] http://www.jdsu.com/products/photovoltaics/products/high-power-optical-data-systems/high-power-optical-data-hipod-system.html

[3] F. Caspers, J. Jaeckel, A. Ringwald; Feasibility and physics reach of microwave cavity experiments searching for hidden photons and axions; to be published; 2009

9. Acknowledgments

Thanks to Erk Jensen and Thomas Bohl for reading the manuscript, checking the English and many helpful comments.

Appendix: datasheet of amplifier used for this experiment

MITEQ

100 Davids Drive, Hauppauge, N.Y. 11788-2034

PROJECT No:
MODEL No: AFD3-0824
SERIAL No: 177628
CUSTOMER:
P.O. No:

IMPORTANT – MUST USE HEAT SINK IF CASE TEMPERATURE EXCEEDS 70°C

SPECIFICATIONS AT 23° C:			
FREQUENCY:	.8 to 2.4 GHz	OUTPUT POWER @ 1dB GAIN COMPRESSION:	+10 dBm
MIN. GAIN:	30 dB	VOLTAGE:	+15 VOLTS
MAX.GAIN FLATNESS:	+/- 1 dB	MEASURED CURRENT:	119 mA
MAX. VSWR INPUT:	2 :1	MAX. NOISE FIGURE:	2.0 dB
MAX. VSWR OUTPUT:	2 :1	HOUSING No:	107940 (163)

NOTE: TEST DATA TAKEN WITH CASE TEMP. OF 23°C

FREQUENCY (GHz)	GAIN (dB)	VSWR IN	VSWR OUT	NOISE FIGURE (dB)	OUTPUT POWER (dBm) (@ 1dB GAIN COMPRESSION)
.80	35.2	1.52	1.36	1.19	+13
1.0	34.8	1.26	1.41	1.00	+13
1.2	34.3	1.69	1.40	.93	+13
1.4	34.3	1.70	1.38	.93	+13
1.6	34.4	1.65	1.34	.98	+14
1.8	34.6	1.58	1.29	1.08	+14
2.0	34.6	1.50	1.28	1.22	+13
2.2	34.7	1.49	1.32	1.32	+14
2.4	34.5	1.53	1.37	1.58	+13

TESTED BY:

DATE: 06/11/90