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DESIGN AND IMPLEMENTATION OF OUTPUT CIRCUITRY FOR MILLIMETER-WAVE DIRECT DETECTION RADIOMETER

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Abstract: This paper presents a design and an implementation of an output circuitry for a millimeter-wave direct detection radiometer. This circuitry is based on commercially available ultra-low-noise op-amp and consist of an active anti-aliasing filter and DC amplifier. The prototype of this circuitry has been realized and evaluated.

Keywords: Millimeter-wave radiometer; Direct detection radiometer; Output radiometer circuitry; Anti-aliasing filter.

1 INTRODUCTION

Millimeter-wave (MMW) radiometers are very sensitive broadband receivers that operate at millimeter wavelengths. They can measure physical temperature or emissivity of objects.

Some of most important applications of MMW radiometry are [1]:

- Hidden weapon and contraband detection;
- Weapon guidance and missile seekers;
- Radio astronomy;
- Remote sensing of atmosphere;
- Remote measurement of temperature;
- Humidity and water vapor measurement from ground and space;
- Etc.

Because radiometers are passive receivers, their use for military purposes is very advantageous since their activity cannot be detected by any means.

MMW radiometers measure the received noise power at the antenna output with very small amplitudes at noise level. For this reason, the use of low-noise output circuits of the radiometer is crucial.

This article describes the construction of low-noise circuits, which are necessary for processing the noise signal from the output of the radiometer. These radiometer output circuits include an anti-aliasing filter and a DC amplifier. The purpose of these circuits is signal conditioning for the analog-to-digital converter (ADC).

2 RADIOMETER FRONT END PROPERTIES

As a radiometric front-end RF module, we used direct detection radiometric module from Farran Technology Ltd. as is shown in Fig. 1.

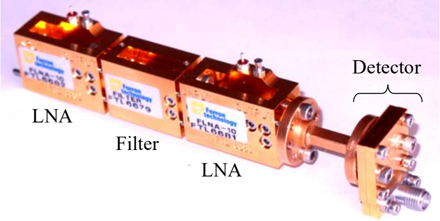

Fig. 1 Direct detection radiometric module
Source: [2].

The block scheme of the radiometric module connection is shown in Fig. 2.

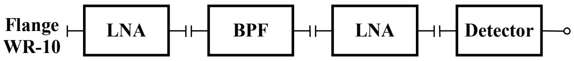

Fig. 2 The block scheme of the radiometric module
Source: author.

where LNA is Low Noise Amplifier, BPF is Band Pass Filter and Detector is diode detector.

The specification of the radiometric module is as follows [3]:

- Frequency: 93 to 96 GHz;
- Total gain: 50 dB (min.), 60 dB (typical);
- Noise figure: 4.5 dB maximum;
- Power supply: +5V DC;
- Filter bandwidth: min. 500 MHz.

These parameters are declared by the manufacturer, but the measured data (specifically the bandwidth of the band pass filter - BPF) are much better as is shown in Tab. 1.

Tab. 1 Radiometer RF frond-end parameters

Circuit	Type	NF [dB]	NF [-]	Gain [dB]
1. LNA	FTL 6681	2.903	1.95	27.348
2. LNA	FTL 6682	2.93	1.96	26.679
BPF	FTL 6679	0.9	1.23	-0.9
RF Front End	---	2.907	1.953	53.127

Source: [2].

The detection diode is a W-band planar detector without applied bias. It is a logarithmic-linear detector based on Schottky diode technology. Minimum sensitivity is approximately 2.2 V/mW. The detected voltage has a positive polarity.

3 THE LIMIT SIGNAL LEVELS AT THE RADIOMETER OUTPUT

When designing a DC (direct current) amplifier, it is necessary to calculate the limit values of the voltage that will be at the output of the radiometric module.

3.1 The maximum voltage value at the radiometer output

Consider the maximum dynamic range of the signal from the radiometer output will be if the temperature of the antenna is $T_A = 0$ K and the temperature of the reference load will be $T_R = 313$ K. The difference between the temperature of the reference load and the antenna will be $\Delta T_{MAX} =$ 313 K. However, we also must include the system noise temperature, too. Temperature ΔT_{MAX} together with the noise temperature of the system T_N corresponds to the power of the radiometer output:

$$\begin{aligned} P_{MAX} &= k_B(\Delta T_{MAX} + T_N)B = \\ &= 1.38 \times 10^{-23} \cdot (313 + 276.254) \cdot 11.7 \times 10^9 = \\ &= 95.141 \times 10^{-12}\ \mathrm{W}. \end{aligned} \tag{1}$$

After amplification by a radiometric module with a gain of $G = 53.127$ dB, we receive a signal at the input of the detector:

$$\begin{aligned} P_{max} &= P_{MAX} G \\ P_{max} &= 95.141 \times 10^{-12} \cdot 10^{\frac{53.127}{10}} = \\ &= 19.5464 \times 10^{-6} = 19.5464\ \mu\mathrm{W}. \end{aligned} \tag{2}$$

Since the sensitivity of the detector is 2.2 V/mW (2200 V/W) [3], then the amplitude of the signal behind the detector at the input of the DC amplifier will be:

$$U_{\max} = 19.5464 \times 10^{-6} \cdot 2200 = 43\ \mathrm{mV_{pp}}. \tag{3}$$

3.2 The minimum voltage value at the radiometer output

The minimum voltage at the radiometer output is reached if $T_A = 0$K. Then the power at the radiometer output will be:

$$\begin{aligned} P_{\min} &= k_B(0\mathrm{K} + T_N)B = \\ &= 1.38 \times 10^{-2}\ .(0 + 276.254) \cdot 11.7 \times 10^9 = \\ &= 44.604 \times 10^{-12}\mathrm{W}. \end{aligned} \tag{4}$$

After amplification by the radiometric module, we get:

$$\begin{aligned} P_{\min\,\mathrm{det}} &= P_{\min}\, G = \\ &= 44.604 \times 10^{-12} \cdot 10^{\frac{53.127^{-6}}{10}} = \\ &= 9.163 \times 10^{-6} = 9.163\ \mu\mathrm{W}. \end{aligned} \tag{5}$$

At the output of the detector, we get:

$$U_{\min} = 9.163 \times 10^{-6} \cdot 2200 = 20.1603\ \mathrm{mV_{pp.}} \tag{6}$$

3.3 Voltage value at the output of the radiometer when measuring a 1K thermal difference

The minimum signal at the output of the radiometer, which should be processed without degradation, is e.g., 1K. This will be if the antenna temperature is for example $T_A = 312$ K and the temperature of the reference load is $T_{ref} = 313$ K. Thus, the minimum signal at the input of the DC amplifier for a resolution of 1K will be:

$$\begin{aligned} \Delta P_{1K} &= k_B(1\mathrm{K})B = \\ &= 1.38 \times 10^{-2} \cdot (1) \cdot 11.7 \times 10^9 = \\ &= 16.146 \times 10^{-14}\ \mathrm{W}. \end{aligned} \tag{7}$$

After amplification by the radiometric module, it will be:

$$\begin{aligned} \Delta P_{out\ 1K} &= \Delta P_{1K} 10^{\frac{G}{10}} = 16.146 \times 10^{-14} \cdot 10^{\frac{53.127}{10}} \\ &= 33.556.10^{-9} = 33.556\ \mathrm{nW}. \end{aligned} \tag{8}$$

At the detector output with a sensitivity of 2200 V/W we get

$$\begin{aligned} U_{1K} &= 33.556 \times 10^{-9} \cdot 2200 = 73.8232 \times 10^{-6} = \\ &= 73.8232\ \mu\mathrm{V_{pp}}. \end{aligned} \tag{9}$$

The Fig. 3 serves to understand these calculations. From the above text the following conclusion can be drawn:

- For the brightness temperature $T_A = 0$ K, the voltage at the detector output will be approx. 20.1603 $\mathrm{mV_{pp}}$.
- For the maximum brightness temperature $T_A = 313$ K, the voltage at the detector output will be approx. 43 $\mathrm{mV_{pp}}$.
- A brightness temperature difference of 1 K will represent a voltage increase at the detector output of 73.8223 $\mu\mathrm{V_{pp}}$.

4 DC AMPLIFIER DESIGN

When designing a DC amplifier, it is necessary to evaluate the influence of its own noises on the radiometer resolution.

4.1 Calculation of the influence of the inherent noise of the DC amplifier

When sampling the signal from the DC amplifier by the A/D converter (ADC), we will apply digital integration with the integration time $\tau = 10$ ms.

This integration time corresponds to a bandwidth of 50 Hz (more details well be explained in Paragraph 5).

As a DC amplifier, we will use an ultra-low-noise operational amplifier (OA) from Analog Devices AD8599. The OA has a spectral voltage noise density of 1.07 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ at a frequency of 1 Hz, and from a frequency of 10 Hz this noise increases to 1.5 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$. The average value of the spectral voltage noise density is 1.285 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$.

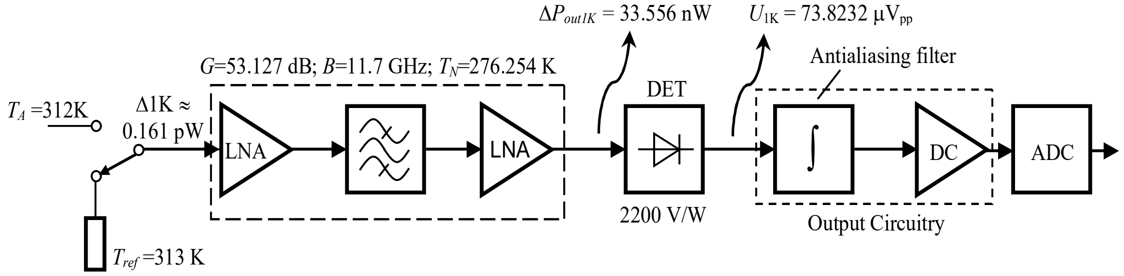

Fig. 3 Power and voltage values on the radiometric module of Farran Technology Ltd.
Source: author.

The noise signal of this OA in the band up to 50 Hz will be:

$$S_N = \sqrt{50} \cdot 1.285 \times 10^{-9} = 9.0863 \text{ nV}. \quad (10)$$

For the resolution of the brightness temperature 1K at the radiometer input, the output of radiometer will give a voltage difference of 43.66 µV. Compared to the used OA noise of 9.0863 nV so this noise will not have a significant effect on the resolution ability of the radiometer.

4.2 Calculation of the DC amplifier gain

Next step is to calculate how much gain should be set on the DC amplifier so that the maximum value reaches 95% of the range of the ADC (for example +/-5V = 10V).

The AD8599 allows to amplify signals with a voltage gain of 110 dB. If we consider that at the maximum voltage from the output of the radiometer is approx. 43 mV and we require 95% of 10 V at the OA output, then its gain should be:

$$G_{OA} = 0.95 \cdot 10/(43 \times 10^{-3}) = 220.9, \quad (11)$$

and by converting to decibels, we get a gain of 46.9 dB.

When measuring the minimum value at the input of the radiometer (for $T_A = 0$ K), we get a signal at the output of the DC amplifier:

$$S_{MIN} = 20.1603 \times 10^{-3} \cdot 220.9 = 4.4534 \text{ V}, \quad (12)$$

and when measuring the maximum value at the input of the radiometer (for $T_A = 313$ K) will be

$$S_{MAX} = 43 \times 10^{-3} \cdot 220{,}9 = 9.4 \text{ V}. \quad (13)$$

For a resolution of 1 K, it will be at the output of the amplifier:

$$\frac{S_{MAX}-S_{MIN}}{313} = \frac{9.4-4.4534}{312} = 15.854 \times 10^{-3} \approx 16 \text{ mV}. \quad (14)$$

Since the ADC has a dynamic range of ±5 V, it is necessary to include a zero-level adjustment circuit before the DC amplifier. This circuit will set the minimum value of the radiometer output to a level close to the lower limit of the range of the ADC (±5V).

5 THE DIGITAL INTEGRATOR

The digital integration of the signal output from the radiometer can be realized numerically in a computer that reads the data from the ADC.

If we were to solve the integrator as an analog one, it would be implemented as an RC low-pass filter. The relations between the noise bandwidth b, the equivalent integration time τ, given by the values of the passive RC elements and the cut-off frequency f_c are determined by the relation [4]:

$$b = \frac{1}{2\tau} = \frac{1}{4RC} = \frac{\pi}{2} f_c. \quad (15)$$

From the above-mentioned relationship, it is possible to calculate that with an integration time of 10 ms (used in actual radiometer), the equivalent bandwidth will be $b = 50$ Hz and the cut-off frequency $f_c = 31.83$ Hz. Even if the integrator will be implemented digitally, it is necessary to place an anti-aliasing filter in front of the ADC. This can be basically implemented as an analog filter (integrator) using an operational amplifier. However, this anti-aliasing filter affects the digital integrator, and for that reason it is necessary to reduce its integration time to approximately half the time of the digital integrator (5 ms for an integration time of 10 ms).

6 REALIZATION OF THE RADIOMETER OUTPUT CIRCUITRY

Due to the necessity of using an anti-aliasing filter at the output of the radiometer detector and its subsequent amplification, the output circuitry of the radiometer was designed and constructed.

The circuit shown in Fig. 4 uses the AD8599 ultra-low-noise operational amplifier, which contains two operational amplifiers (OAs) in one package.

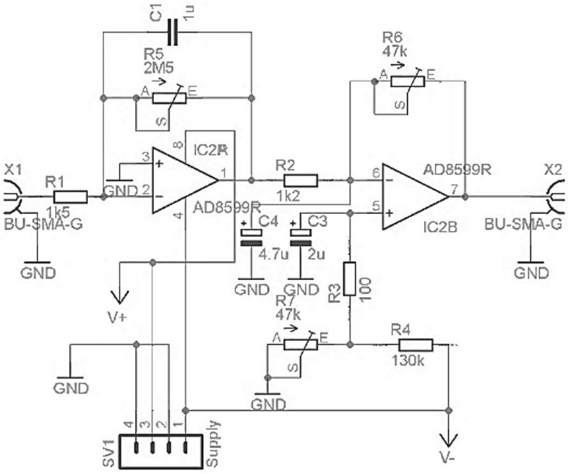

Fig. 4 Wiring diagram of radiometer output circuitry
Source: authors.

The first OA (IC2A) is wired as an integrator with an active element, and it is used as an antialiasing filter (first-order filter). The integration time is set by capacitor C1 and trimmer R5. The time constant is given by $\tau = C_1R_5$, which corresponds to the corner angular frequency $\omega = 1/(C_1R_5)$. With the specified parameters of the components, the maximum integration time is 2.5 seconds. The gain of this first stage is:

$$G_1 = \frac{R_5}{R_1}. \quad [-] \tag{16}$$

Frequency response of this antialiasing filter is in Fig. 5.

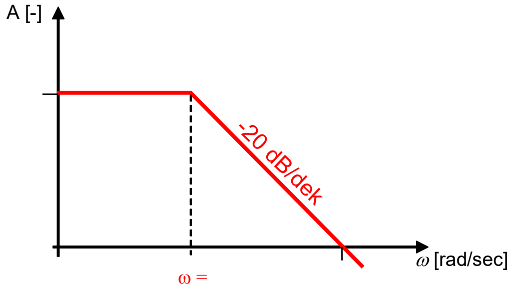

Fig. 5 Frequency response of antialiasing filter
Source: author.

The second OA (IC2B) represents a DC amplifier, where the gain of the amplifier is adjusted by the trimmer R6. The gain of the DC amplifier is:

$$G_2 = \frac{R_6}{R_2}. \quad [-] \tag{17}$$

Trimmer R7 serves to set the zero level at the output of the DC amplifier. The output of the DC amplifier is connected to an ADC. After A/D conversion, the signal is processed in the computer.

The Fig. 6 shows the prototype of the low-frequency circuitry.

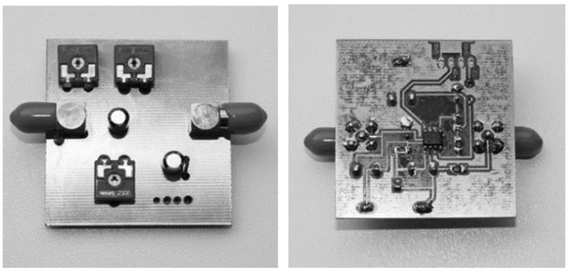

Fig. 6 Photography of top and bottom side of the low-frequency circuitry
Source: author.

7 RADIOMETER OUTPUT SAMPLING

The proposed radiometer is used to measure temperatures in the range of 0 K to 313 K with a sensitivity of about 0.05 K. It is unacceptable that we worsen these parameters by inappropriate digital processing.

For sampling, we will use an 8-channel, 16-bit AD converter (ADC) from National Instruments, type NI USB-6221. It allows measuring in the ranges ±1V, ±2V, ±5V and ±10V.

Sixteen bits allow the resolution of 1 to 65,536 quantization levels. To prevent overflow (exceeding the range of the ADC) we will use only 95% of the input range of the converter. It allows sampling with a resolution of $0.95 \cdot 65{,}536 = 62{,}295$ quantization levels.

To sample the temperature range of 313 K, we can achieve this with precision:

$$313\ \mathrm{K} \,/\, 62{,}295 = 0.005\ \mathrm{K}, \tag{18}$$

thus, due to sampling, the sensitivity of the radiometer will not deteriorate.

If we need to achieve an integration time of 10 ms, then we need to set the sampling rate of the ADC when capturing 1024 samples of the input signal:

$$f_s = \frac{1024}{\tau} = \frac{1024}{10\times10^{-3}} = 102{,}400 = 102.4\ \mathrm{kHz}. \tag{19}$$

The used ADC allows to record with a sampling frequency f_s of a maximum of 250 kHz. We choose 100 kHz as the sampling frequency. It follows the minimum integration time will be:

$$\tau = \frac{1024}{f_s} = \frac{1024}{100\times10^3} = 10.24\ \mathrm{ms}. \tag{20}$$

The direct detection radiometer sensitivity is like a total power radiometer sensitivity and is given by [4]:

$$\Delta T = \frac{T_{ref}+T_N}{\sqrt{B\tau}}, \tag{21}$$

where T_{ref} is a temperature of reference load (313 K), B is a radiometer front-end bandwidth (measured bandwidth is 11.7 GHz). T_N is overall noise temperature of radiometer front-end components and can be calculated by [6]:

$$T_N = 290(NF - 1) = 290(1.9526 - 1) = \\ = 276.254\ \text{K}. \tag{22}$$

where NF is a noise temperature of the radiometer front-end (its value is in Tab. 1.).

To understand above mentioned variables and their values see Fig. 3.

The resulting sensitivity of the radiometer according to (21) is:

$$\Delta T = \frac{313+276.254}{\sqrt{11.7\times10^{9}\cdot10.24\times10^{-3}}} = 0.0538\ \text{K}. \tag{23}$$

Even though integration time is set to 10 ms we can see the resulting sensitivity of the radiometer is very high.

8 CONCLUSION

In this article, we presented the design and construction of the output circuitry for the millimeter- wave radiometer.

The concept of this circuitry was based on calculations of the minimum and maximum value of the output voltage from the radiometer detector for temperatures from 0 K up to 313 K.

The output circuitry uses commercial ultra-low-noise operational amplifier AD8599 that contains two operational amplifiers in single package.

It was shown that the noise of this OA does not have a significant effect on the resolution of the radiometer used.

The presented circuitry is a perspective solution for millimeter-wave or microwave radiometers.

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