AC-DC Transfer Difference Measurements using a Frequency Output Thermal Converter

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Abstract: This paper presents the design of a Frequency Output Thermal Converter (FOTC), built using commercially available discrete components. The FOTC structure consists of a discrete resistor as heater element with a thermistor connected to an oscillator as temperature sensor. The AC-DC transfer difference of the FOTC was measured by direct comparison with calibrated TCs.

Keywords: ac-dc voltage transfer, thermal converters, frequency measurements.

1. INTRODUCTION

Despite the recent developments in Josephson-based AC voltage calibration systems [1], the accurate characterization of the root-mean-square (rms) values of time-varying (ac) signals is still most widely done by the use of thermal converters (TCs). A basic TC consists of a heater structure and a temperature sensor, which allows the comparison of ac and dc quantities [2]. We are working on an alternative TC design, using a discrete surface-mount device (SMD) resistor as heater element and a thermistor connected to an oscillator as temperature sensor [3]. In this work we present the results obtained with an improved structure.

2. FREQUENCY OUTPUT THERMAL CONVERTER

The basic structure of the FOTC (Figure 1) consists of two main blocks: the *thermal converter* and the *oscillator*. The heater element is a SMD resistor and the temperature sensor is a NTC (negative temperature coefficient) thermistor. The output of the thermistor is connected to an oscillator. The output frequency of the oscillator is proportional to $1/(R_{ntc}C)$, where C is a fixed capacitor and R_{ntc} is the output resistance of the thermistor, which is inversely proportional (but not linearly) to the temperature of the heater. Thus, this composition of proportionality constants results in an output frequency proportional (but not linearly) to the input power (i.e., the RMS value of the input voltage).
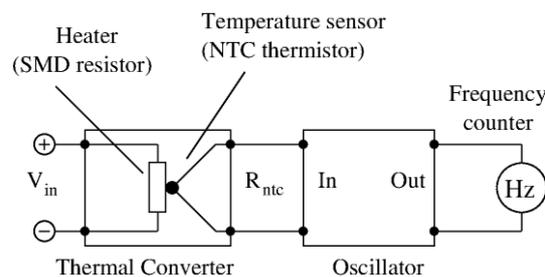

Figure 1. FOTC basic structure.

2.1. Thermal Converter

The layout of the thermal converter is presented in Figure 2. The thermal converter was built using a printed circuit board (PCB) substrate, rated for frequencies up to 40 GHz. A microstrip

transmission line was designed for characteristic impedance (Z_0) of 50 Ω, matching with the nominal value of the SMD resistor used as heater element.
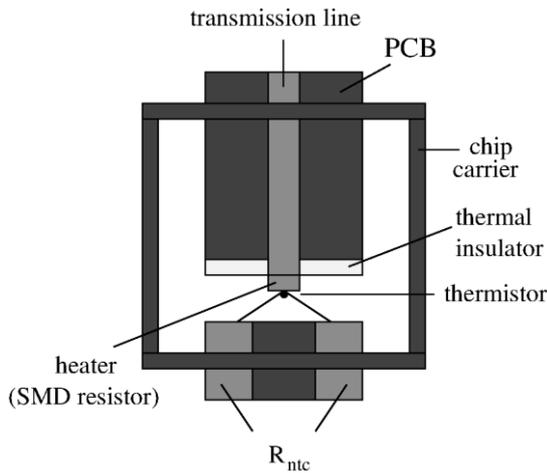
(a) Top view.
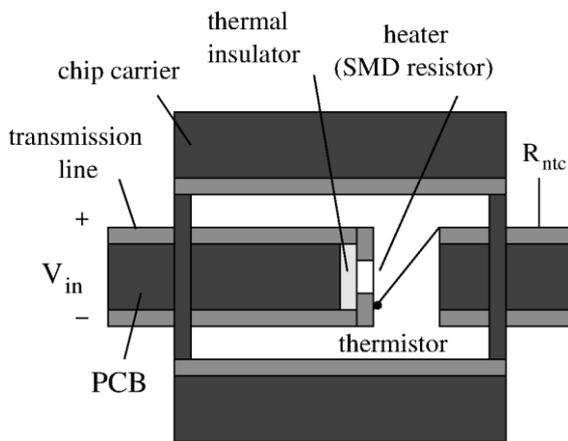
(b) Side view.

Figure 2. Thermal converter layout.

The heater element (a SMD 0402 form factor resistor, 50 Ω) was mounted like a line terminating resistor, perpendicular to the substrate. A layer (of approximately 1.5 mm) of thermal insulating material (expanded polystyrene) was used to improve the thermal resistance. The temperature sensor is a micro-bead NTC thermistor (0.33 mm bead diameter), fixed next to the low potential terminal of the heater resistor using epoxy glue mixed with

alumina, in order to improve the thermal contact between heater and temperature sensor.

A chip carrier structure was built using the same PCB substrate used for the main structure. With the chip carrier closed, only the input terminals of the heater and the output terminals of the temperature sensor are accessible, as shown on Figure 2.

2.2. Oscillator

A comparison of several oscillator structures showed that the circuit of Figure 3 provides the best stability [4]. The basic topology of the oscillator is composed by an integrator block, a comparator block and a double pole double throw (DPDT) switch connected to stable voltage references ($+V_{ref}$ and $-V_{ref}$).
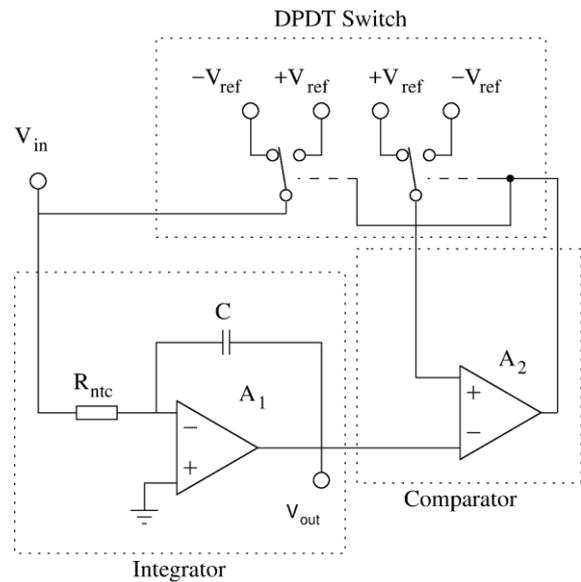

Figure 3. Oscillator topology.

The fractional frequency ($\Delta f/f_0$) of the oscillator was measured using a frequency counter, with averaging time (τ_0) set to 0.1 s. Figure 4 shows the fractional frequency variations over a period of 15 minutes (9000 samples).
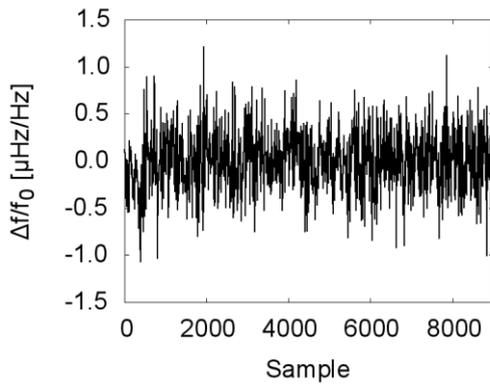
Figure 4. Frequency stability (15 minutes).

3. RESULTS

3.1. Measurement setup

The AC-DC transfer difference of the FOTC was determined by direct comparison with calibrated Planar Multijunction Thermal Converters (PMTCs) of our reference system [5]. The measurement setup is presented on Figure 5. The system is fully-automated, controlled by locally developed control software.
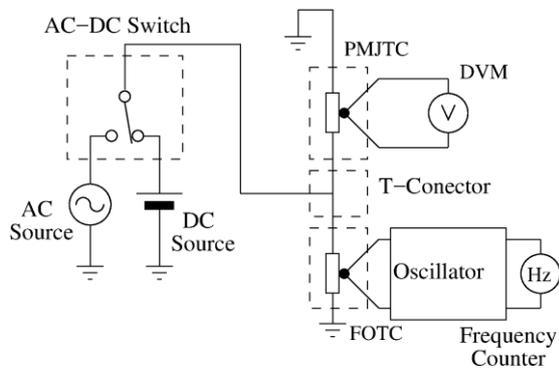

Figure 5. Measurement setup.

One major drawback of using a thermistor instead a thermocouple as temperature sensor is an undesirable sensitivity to fluctuations of the ambient temperature (the differential nature of the thermocouple minimizes this issue). To overcome this, a temperature controlled air bath was used. In future works we plan to develop a compensation circuit or an active temperature control to avoid this limitation.

3.2. Measurement results

The AC-DC transfer difference of the FOTC δ_{FOTC} was measured at 1 V level using a calibrated 90 Ω PMJTC as standard. The results are presented in Table 1, where δ_{FOTC} is the AC-DC transfer difference of the FOTC, δ_{PMJTC} is the AC-DC transfer difference of the PMJTC, and $U(\delta_{FOTC})$ and $U(\delta_{PMJTC})$ are the corresponding measurement uncertainties. δ_M is the measured AC-DC transfer difference (relative), and σ is the standard deviation of the measurement.

Table 1. AC-DC transfer difference in µV/V (at 1 V level).

f [kHz]	0.065	0.12	1	10	100	1000
δ_{PMJTC}	0.4	0.0	0.0	1.0	12.0	58
$U(\delta_{PMJTC})$	1.3	1.3	1.5	1.5	3.5	19
δ_M	0.1	-2.1	-1.4	-1.3	7.6	86.6
σ	1.4	0.4	1.9	2.7	0.5	1.0
δ_{FOTC}	**0.5**	**-2.1**	**-1.4**	**-0.3**	**19.6**	**144**
$U(\delta_{FOTC})$	**1.6**	**1.6**	**1.9**	**2.4**	**3.9**	**34**

Table 2. AC-DC transfer difference in µV/V (at 1.5 V level).

f [kHz]	0.065	0.12	1	10	100	1000
δ_{PMJTC}	0.5	0.1	0.1	0.8	3.3	-11.1
$U(\delta_{PMJTC})$	1.3	1.3	1.5	1.5	3.5	19.0
δ_M	-0.2	-0.9	-0.3	1.4	20.9	181.2
σ	1.0	0.6	0.8	0.7	1.0	4.9
δ_{FOTC}	**0.3**	**-0.8**	**-0.2**	**2.2**	**24.2**	**170**
$U(\delta_{FOTC})$	**2.5**	**2.5**	**2.6**	**2.6**	**4.3**	**22**

At 1.5 V level, the FOTC AC-DC transfer difference was measured using a 180 Ω PMJTC as standard. The results are presented in Table 2, following the same naming convention.

The AC-DC transfer difference of the FOTC does not show a significant level dependence, as we can see comparing the results obtained at 1 V and at 1.5 V, considering the

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uncertainties. For frequencies up to 10 kHz the AC-DC transfer difference is small, typically smaller than 3 µV/V.

3.3. Validation

In order to validate the results, we did measurements of a second PMJTC, following the scheme of Figure 6.
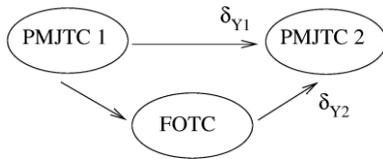

Figure 6. Validation scheme.

In the first step we have determined the AC-DC difference of the PMJTC 2 directly against the PMJTC 1 (δ_{Y1}). Then, the AC-DC difference of the FOTC was measured using the PMJTC 1 as standard, and finally the AC-DC difference of the PMJTC 2 was obtained using the FOTC as standard (δ_{Y2}).

To validate the results, we have calculated the normalized error (E_n) using the result δ_{Y1} as reference:

$$E_{\mathrm{n}} = \frac{\delta_{Y2} - \delta_{Y1}}{U(\delta_{Y2})^2 + U(\delta_{Y1})^2} \qquad (1)$$

When $E_n < 1$, the result is considered validated. The results are presented in Table 3.

Table 3. Validation of the results at 1 V (AC-DC transfer differences in µV/V).

f [kHz]	0.065	0.12	1	10	100	1000
$\delta_{\mathbf{Y1}}$	0	0	0	0	7	32
$U(\delta_{\mathbf{Y1}})$	1	1	2	2	4	34
$\delta_{\mathbf{Y2}}$	1	0	0	1	9	45
$U(\delta_{\mathbf{Y2}})$	1	2	2	2	4	44
$E_{\mathbf{n}}$	**0.1**	**0.1**	**0.2**	**0.2**	**0.4**	**0.2**

4. CONCLUSION

We have presented a Frequency Output Thermal Converter, built using commercially available discrete components, that can be be used as an AC-DC voltage transfer standard.

Future works:

- Improve the TC immunity to ambient temperature fluctuations;

- Improve the design and build a high frequency optimized TC to extend the traceability to frequencies higher than 1 MHz.

5. REFERENCES

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