microbridge

TECHNICAL SUMMARY

Rejustor Noise Analysis

1 Introduction

The ***Rejustor*** from Microbridge Technologies represents a major technological improvement for analog compensation. ***Rejustors*** are typically used in applications where high precision and set-on-test adjustability is necessary. The application note examines the noise characteristics of the Rejustor compared with poly-silicon resistors and precision metal-film resistors.

The *Rejustor* is an analog adjustable resistor. These units can be adjusted multiple times and always maintain the last adjusted state alone or in-circuit, even if they are placed in storage for extended periods. The resistance change is permanent and after adjustment, these passive devices require no power to hold their precise value.

Analog designers have traditionally been required to make significant compromises in order to achieve precision in applications where adjustment is required during the manufacture and test phase of production. Choices include hand-sorting precision resistors, turning a screw on a trim-pot, using a digital-pot or a using the Rejustor to meet the specific calibration requirement for each unit. Hand-sorting precision resistors thus far has provided the highest precision and the lowest noise but increases labor and manufacturing time. Multi-turn pots reduce labor requirements but significantly increase noise. High reliability pots tend to be considerable more expensive than many manufacturers can afford. Digital pots facilitate automated test and calibration, however these devices are noisy, offer limited bandwidth and assume the application includes other digital technologies to provide the necessary serial port and memory.

The Rejustor completes the evolution of analog adjustment. It offers the lowest noise of any adjustable resistor technology and the highest bandwidth. With Rejust-it calibration tools, the calibration is easy to automate, increasing production through-put and efficiency.

2 Experimental Setup

For clarification on the equations governing noise theory in resistors consult Appendix A at the end of this note. Refer to equations 12-15 under Noise Power Spectral Density in the Appendix which are used in the following analysis.

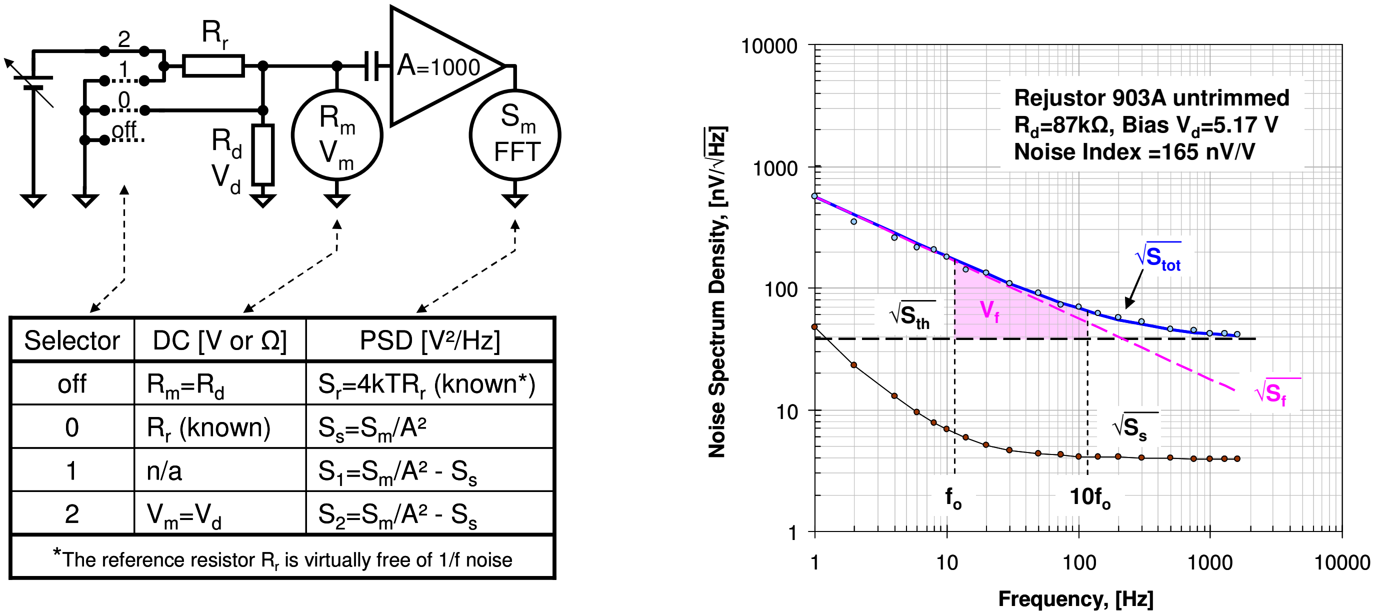
In this study the noise characterization of Rejustor samples was performed in the Microelectronics Research Laboratory of the Electrical and Computer Engineering Department of McMaster University (Hamilton, Canada). The Rejustor samples were wirebonded in ceramic packages and biased with voltages between 1-10 V depending upon device resistance, not exceeding the specifications for maximum power. Samples of adjusted Rejustors were analyzed in comparison, as well as suitably doped untrimmed polycrystalline silicon devices. In addition, comparisons were made to commercially available discrete devices known to possess excellent noise characteristics, with tests of noise in samples of precision metal-film and oxide-film resistors.

Figure 1 outlines the test setup and the major steps in the measurement. It also shows a typical outcome from noise measurements of a Rejustor. Details related to calibration and accuracy verification and traceability are omitted for clarity. The setup and the procedures are traceable and based on principle described in MIL-STD-802 (Method 308). In particular, the noise index is obtained by using equation 15 (developed in Appendix A)..

DC and noise measurements are taken in four steps for each sample. When the selector is at position “off”, then the device resistance R_d is measured. From the known value R_r of the reference resistor, the noise voltage PSD of the reference resistor is found from:

$$S_r = 4kTR_r\,, \tag{1}$$

since R_r is virtually free of 1/f noise at the low biasing conditions used during the measurement.



Selector	DC [V or Ω]	PSD [V²/Hz]
off	$R_m=R_d$	$S_r=4kTR_r$ (known*)
0	R_r (known)	$S_s=S_m/A^2$
1	n/a	$S_1=S_m/A^2 - S_s$
2	$V_m=V_d$	$S_2=S_m/A^2 - S_s$

*The reference resistor R_r is virtually free of 1/f noise

Figure 1: Outline of Test Setup and Measurements (90kΩ Rejustor)

When the selector in Figure 1 is at position “0”, then the noise voltage PSD of the system noise floor is measured. The reading S_m from FFT analyzer was referred to the input of the amplifier by dividing by the square of the voltage gain A of the amplifier, as stated in the table of Figure 1. The system noise floor S_s is shown in the right hand plot of Figure 1.

When the selector is at position “1”, then no bias is applied to the device, and the FFT analyzer reads the sum of thermal noise in R_r and R_d, as well as the system noise floor. This step also comprises the first measurement in MIL-STD-802 (Method 308). After referring the measured PSD to amplifier input and subtraction of system noise, the spectrum S_1 is obtained as given in the table of Figure 1, and the thermal noise in the device under test is:

$$S_{th} = S_1\left(1+\frac{R_d}{R_r}\right)^2 - S_r\left(\frac{R_d}{R_r}\right)^2, \quad \text{no bias,} \tag{2}$$

The values match closely with the predictions of equation (7), as illustrated in the right hand plot of Figure 1 by a horizontal black dash-line. The terms in the brackets of equation (2) reflect the fact that R_r and R_d are connected together.

When the selector in Figure 1 is at position “2”, then the device is biased by the battery and the test comprises the second measurement in MIL-STD-802 (Method 308). As given in the table of Figure 1, the reading V_m from the DC voltmeter is the biasing voltage V_d on the device under test, and S_2 is the noise PSD across R_d, which is compensated for the system noise floor S_s. The total noise voltage PSD of the device is then:

$$S_{tot} = S_2\left(1+\frac{R_d}{R_r}\right)^2 - S_r\left(\frac{R_d}{R_r}\right)^2 \text{, at bias } V_d. \qquad (3)$$

A typical result for S_{tot} is shown in the right hand plot of Figure 1 by circles with blue solid line through them. Again, the terms in the brackets of equation (3) reflect the fact that R_r and R_d are connected together. Results for S_{tot} of Rejustors and resistors obtained at this step are presented in following figures.

The excess noise voltage V_f in a frequency decade is then determined according to eq. (12), by:

$$V_f = \sqrt{\int_{f_o}^{10f_o}\left(S_{tot} - S_{th}\right) df} = \left(1+\frac{\mathrm{R_d}}{\mathrm{R_r}}\right)\sqrt{\int_{f_o}^{10f_o}\left(S_2 - S_1\right) df} \quad , \qquad (4)$$

Where f_o is chosen so that $10f_o$ is below or close above the corner frequency between 1/f noise and white noise in S_{tot} of the device under test. A typical result for V_f is shown in the right hand plot of Figure 1 by the area highlighted in pink color with left-right boundaries f_o and $10f_o$ and top-bottom boundaries S_{tot} and S_{th}, respectively. The tilted pink dash-line in this plot shows the voltage PSD of 1/f noise, $S_f = S_{tot} - S_{th}$, and corresponds to equation (12).

Finally, the noise index NI of the device under test is determined according to equation (15), by

$$NI = \frac{V_f}{V_d}\left(\times 10^6 \mu V/V, or \times 10^9 nV/V\right). \qquad (5)$$

The above procedure has been repeated for all samples and biasing conditions, and the results for NI in the samples are summarized in Figure 5.

3 Results

A typical outcome from noise measurements of Rejustors is shown in the right-hand plot of Figure 1. Representative spectra for the total noise S_{tot} taken from different samples with similar resistances $R_d \approx 10k\Omega$ and at similar bias $V_d \approx 4.3V$ are given in Figure 2, along with the system noise floor, for comparison. The metal film and oxide film resistors are discrete, rated for ¼ W, and therefore large in size, while the Rejustor sample is miniature, having two Rejustors on a die that is normally mounted in SOIC or QFN package.

Nevertheless, the Rejustor outperforms the oxide film resistor with approximately 30% (2.5dB) lower 1/f noise. Certainly, the metal film resistors exhibit very low 1/f noise, as it is well established in the practice, but their geometry does not allow for use at microwave frequencies, while the Rejustors can be used in this frequency range.

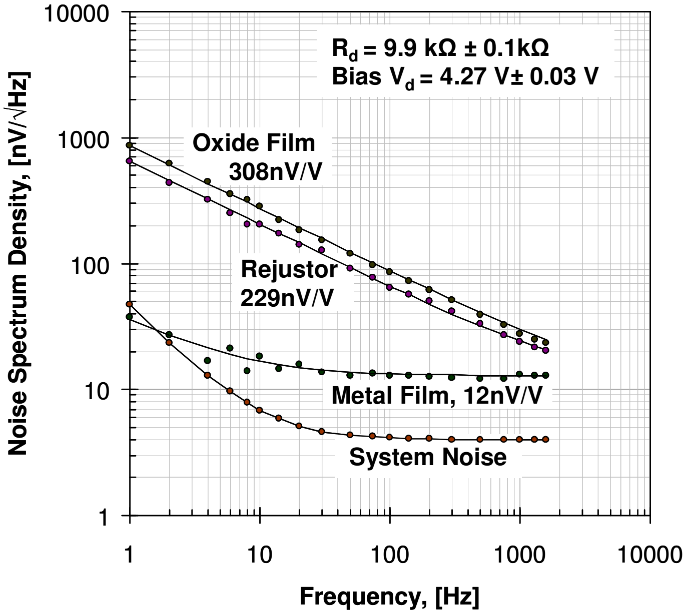


Figure 2: Noise Spectra of Different Samples with Similar Resistances (10kΩ devices)

A comparison between a Rejustor and a polycrystalline silicon resistor similar to those embedded in integrated circuits, is shown in Figure 3. Both devices have similar resistances of about R_d≈10kΩ, but they have been measured at different bias voltages, V_d=3.2V for the Rejustor and lower V_d=1.05V for the poly-Si device, since the latter was a very tiny resistive structure. Even at these conditions, <u>the 1/f noise of the Rejustor is much lower than in the polycrystalline silicon device</u>.

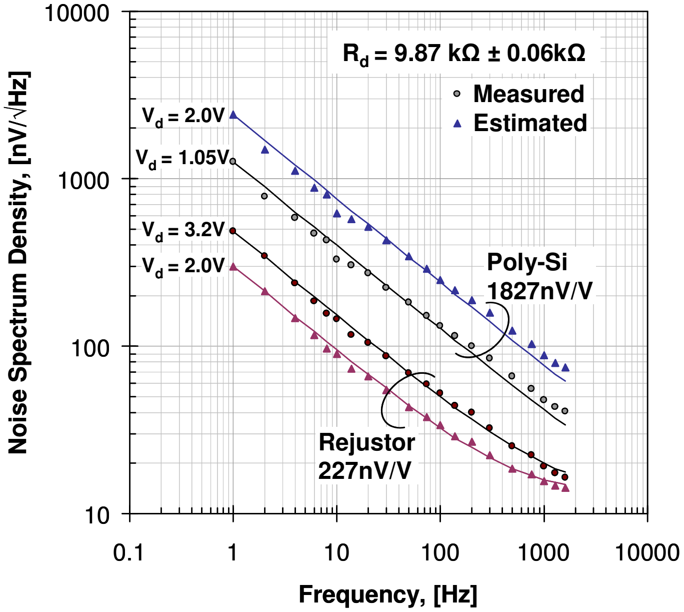


Figure 3: Noise Spectra of Rejustor and Polycrystalline Silicon Resistor with Similar Resistance (10kΩ devices)

For a fair comparison, however, one should examine noise spectra at same bias. This normalization is shown with triangles in Figure 3 for target bias of V_d=2V. The calculation was performed utilizing equation (11), in which K_F was determined from the noise index according to equation (15). Since the 1/f noise voltage is proportional to the bias, then the noise of the Rejustor decreases at the target V_d=2V, which is lower then the bias voltage V_d=3.2V during measurement, while similarly the noise in poly-Si device increases at the target V_d=2V, because the target voltage is higher than the bias voltage V_d=1.05V during measurement. Consequently, the noise from Rejustor at low frequency would be much lower than the noise from poly-Si device at similar bias of the devices, by a factor of 8x, which is the ratio of the noise indexes of the two devices.

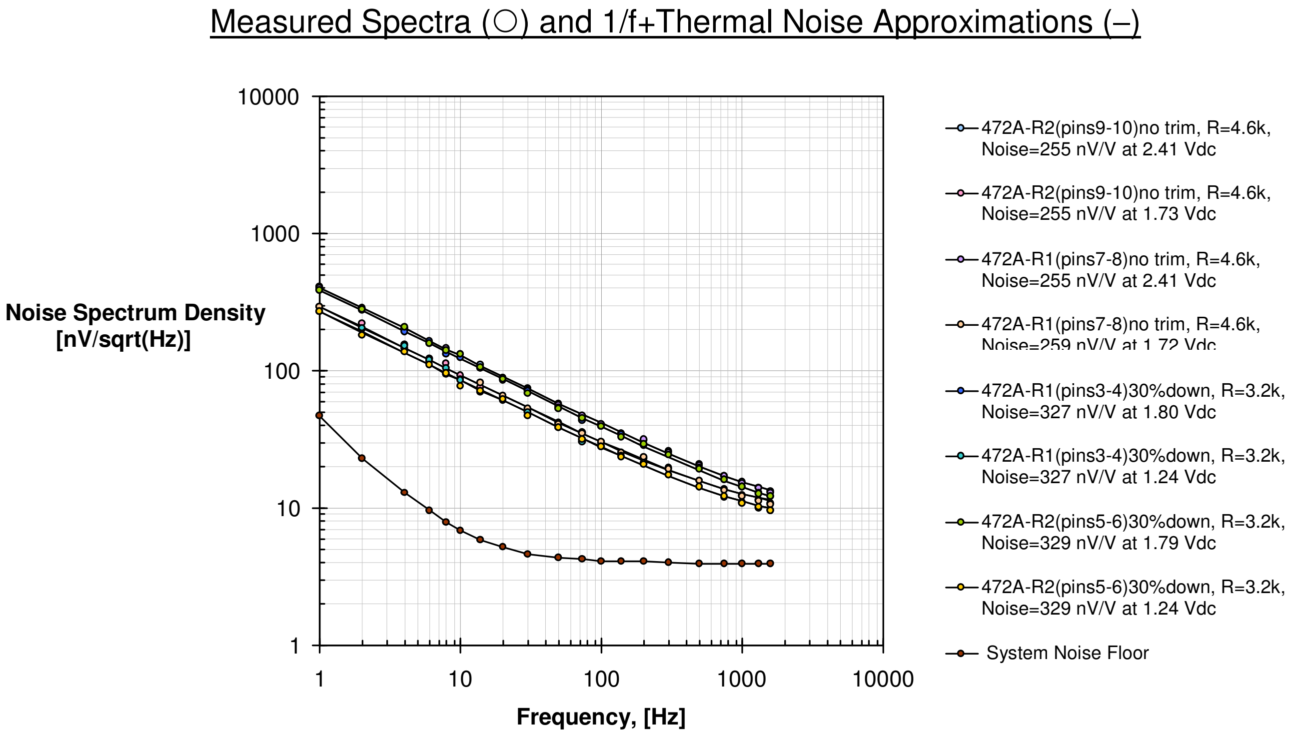


Figure 4: Data Obtained from 4.7kΩ Rejustor Samples

Figure 5 summarizes the results for noise index of all Rejustor samples measured in this study. The noise index of Rejustors is in the range of 100–200nV/V, and it is higher when the resistance of the Rejustor is lower, and vice versa. For approximate prediction of the 1/f noise in Rejustors from standard series, one can use the trend shown in the figure. For example, for Rejustors MBD-103-AS adjusted to 8.0kΩ, one would expect noise index:

$$NI = 1377\left[\frac{nV}{V}\right]\left(\frac{8000\Omega}{1\Omega}\right)^{-0.2} = 228.2\,\mathrm{nV/V}\ . \qquad (6)$$

This value is in the range typical for discrete resistors used commonly in industry. For example, referring to Figure 5, a 10k/5%/0.125W oxide film resistor has noise index of about 300nV/V (as shown by a square), precision metal film resistors have lower 1/f noise (indicated by the triangles) and integrated polycrystalline silicon resistors have higher 1/f noise (depicted by diamonds).

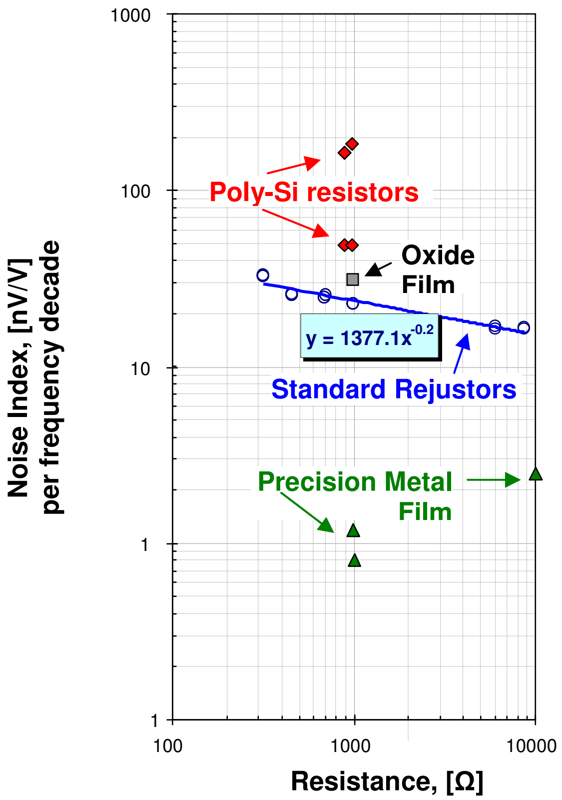


Figure 5: Summary for Noise Index of Investigated Samples

4 Summary

The results indicate that:

- Rejustors produce approximately 10x more noise than low-noise precision metal film resistors.
- Rejustor noise is as good or better than a conventional oxide film resistor or polysilicon resistors tested in this study
- There is a noise variation with Rejustor resistance with a $R^{-0.2}$ dependence that is primarily due to geometrical considerations involved with creating the disparate resistances of the standard product tested in this study. High resistance Rejustors have lower noise levels than low resistances, in general within the same product line
- No bias dependence of the Noise Index is found in Rejustors, which is consistent with behavior of 1/*f* noise in resistors
- No bias dependence of white noise is observed in Rejustors, which indicates that there is no sign of shot noise, and again is consistent with the behavior of thermal noise in resistors
- Rejustor noise increases slightly after adjustment, in part due to the associated decrease in resistance. More study is necessary to determine what other factors may be contributing to the small noise increase after adjustment.

5 Conclusion

Metal film resistors provide the lowest noise and highest bandwidth of all available resistors. However, they lack adjustability for set-on-test adjustment and geometry renders them inferior at Rf frequencies. Rejustors provide superior performance compared to standard poly-silicon resistors and oxide film resistors. The Rejustor has the lowest noise combined with the ability to automate high-precision adjustments.

Rejustors provide both the highest bandwidth and the lowest observed noise for an adjustable resistor technology. It can be concluded that Rejustors are the best choice for set-on-test adjustment in precision analog circuits.

APPENDIX A
Equations Governing Theoretical Noise in a Resistor

A.

Theoretical Noise in a Resistor

There are several forms of noise which are inherent in materials and devices that pass a current. These can be described as thermal noise, shot noise, 1/f noise and generation-recombination noise. The dominant contributions in resistors are from thermal noise and 1/f noise, the latter increasing with bias and dependent on materials, design and fabrication of the resistors.

1. Thermal Noise

The thermal noise is fundamental, it originates from the random thermal motion of carriers, and it is present wherever there is conduction in a material or structure, such as in a discrete, film, a polysilicon resistor, and, consequently, in the Rejustor. The power spectrum density (PSD) of thermal noise, S_{th}, is uniform as a function of the frequency, as depicted by solid black line in Figure 6, and, therefore, the thermal noise is described as “white”, in analogy to the spectrum of white light. The voltage PSD of the thermal noise is given by

$$S_{th} = V_{th}^2 = 4kTBR \,, \tag{7}$$

where kT is the product of the Boltzmann constant k and absolute temperature T, B the bandwidth of the measurement in Hz and R is the resistance of the conductor, that is, of the Rejustor. The thermal noise is bias independent until the resistance R is significantly changed by self-heating or other means when the power dissipation on the Rejustor exceeds the specified rated power. Noise measurements have quantified that thermal noise is present in Rejustor samples precisely according to equation (7).

2. Shot Noise

Other sources of white noise could be due to the discrete nature of the current, if the carriers have to overcome a barrier and then are accelerated by the electric field, resulting in current “shots”. The corresponding shot noise is bias dependent, having current PSD given by;

$$S_{sh} = 2qI_{DC} \,, \tag{8}$$

where q is the electron charge and I_{DC} is the average (DC) current. No current dependence was found for the white noise in Rejustors, which is the obvious case for resistors. This means that there is no shot noise in Rejustors.

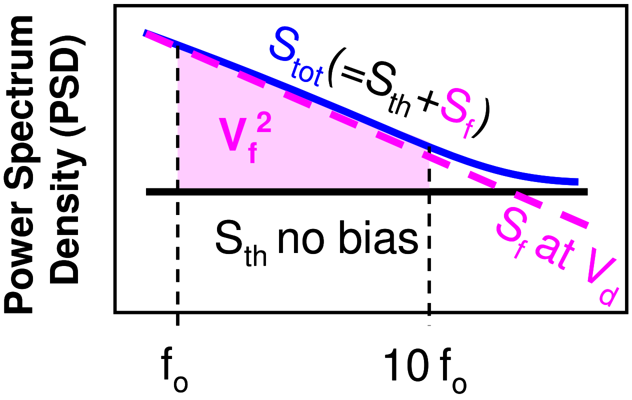


Figure 6: Low frequency noise in resistors

3. 1/f Noise

While the white thermal noise is present at all frequencies, the dominant contribution to the noise at low frequencies is due to 1/f noise, known also as flicker noise, or pink noise, again in analogy with the color of light with 1/f spectrum. The flicker noise S_f is “on top” of thermal noise, as depicted in Figure 6 by pink dash-line, and it occurs and increases in magnitude when the device is increasingly biased to higher levels. Therefore, the 1/f noise is termed as *excess current noise in resistors* by Standard MIL-STD-202G (Method 308). Despite deviations in different electronic devices, the PSD of 1/f noise in resistors is a quadratic function of bias and inversely proportional to the frequency f. The flicker noise voltage PSD, S_f, rewritten in form normalized to the bias voltage V_d, is:

$$\frac{S_f}{V_d^2}=\frac{K_F}{f}, \tag{9}$$

where K_F is known as the generic flicker noise parameter in SPICE models. By dividing the left-hand side of the equation on the square of the device resistance R_d, one can write the equivalent equation for normalized current noise as:

$$\frac{S_{If}}{I_{DC}^2}=\frac{K_F}{f}, \tag{10}$$

where $S_{If}=S_f/(R_d)^2$ is the flicker noise current PSD, $I_{DC}=V_d/R_d$, and K_F is the same as in equation (9).

4. Generation-Recombination Noise

Generation-recombination noise is not observed in Rejustors, and it is omitted from this application note.

5. Noise Power Spectral Density

As follows from equations (7) and (9), at given voltage bias V_d, the voltage PSD of the total noise in Rejustor is:

$$S_{tot}=S_{th}+S_f=4kTBR+\frac{K_F}{f}V_d^2, \tag{11}$$

and S_{tot} is shown with solid blue line in Figure 6.

The shaded area in the figure is for low frequency band of one decade from f_o to $10f_o$, and it depicts the excess noise voltage V_f., which can be found from the difference $(S_{tot}-S_{th})\equiv S_f$, according to:

$$V_f^2 = \int_{f_o}^{10f_o} (S_{tot} - S_{th}) df = \int_{f_o}^{10f_o} S_f df = \int_{f_o}^{10f_o} \frac{K_F}{f} V_d^2 df = [K_F \ln(10)] V_d^2 . \tag{12}$$

The product of K_F by natural logarithm of 10 is related to the noise index in Standard MIL-STD-202G (Method 308), as discussed below.

As evident in equations (9) and (10), one needs to measure PSD of noise in order to obtain K_F. Such measurement is slow, uses expensive equipment, requires numerical post-processing of data, and it is not suitable for industrial testing of resistors. Therefore, method 308 in MIL-STD-202G has standardized measurement of noise voltage V_f in a frequency band of one decade, from f_o to $10f_o$, as illustrated in Figure 6. Two noise measurements are required by this method. First measurement is without bias, thus S_f=0, and this measurement will indicate the thermal noise and the system noise V_s in the frequency band, e.g.

$$V_1^2 = S_{th}(10f_o - f_o) + V_s^2 . \tag{13}$$

The second measurement is with bias voltage V_d across the device, reading the sum of the total noise and the system noise; that is:

$$V_2^2 = \int_{f_o}^{10f_o} S_f df + S_{th}(10f_o - f_o) + V_s^2 = [K_F \ln(10)] V_d^2 + S_{th}(10f_o - f_o) + V_s^2 . \tag{14}$$

Subtracting the last two equations, one obtains the same result in equation (12). Rewritten in normalized form, the expression for the noise index (NI) is:

$$NI = \frac{V_f}{V_d} = \frac{\sqrt{V_2^2 - V_1^2}}{V_d} = \sqrt{K_F \ln(10)} . \tag{15}$$

Method 308 in MIL-STD-202G utilizes the last equation in standard setup and procedure, which includes free-of-flicker-noise reference resistor connected in series between free-of-noise (battery) supply and device under test, band-pass filter, true-RMS voltmeter with logarithmic readout and tables for test conditions and corrections.

The noise characterization of Rejustors presented this application note comply with the standard and are enhanced to provide measurements of noise spectra and noise indices at low bias. The measurements have been taken on standard product Rejustor samples ranging in resistance from 4.7 kΩ to 90 kΩ. It has been found that the noise index of Rejustors is lower than integrated polysilicon resistor samples similarly tested and the results are comparable to discrete resistors used in industry.