EDGES MEMO #072

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To: EDGES Group

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Subject: Balun model and measurements

The edges balun was outlined in EDGES Memo 43. This design is similar to the ferrite-load balun (F.H. Raab, IEEE, 2007) but has the advantage of being balanced with very high common mode rejection.

A] Circuit model

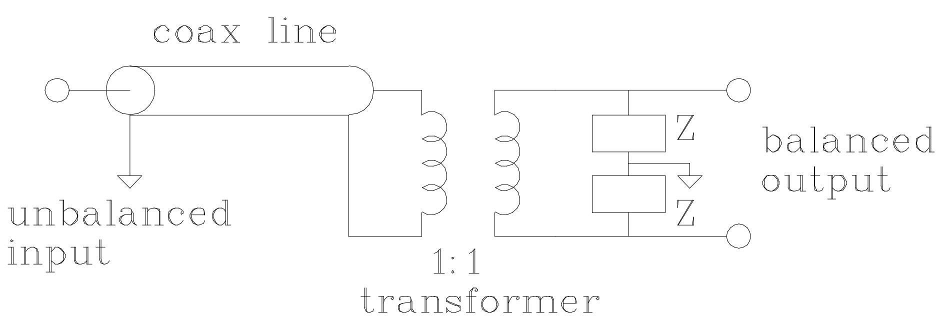

Figure 1. Balun circuit model.

The 50Ω line length is equal to the length of coax inside the ferrite cores. Z is the impedance of a single turn through the ferrite cores. A single material 28 NiZn ferrite core (Steward 28B0592-00) has an impedance of about 600 ohms (mostly resistive) in the frequency range 50 to 100 MHz.

It is not straight forward to accurately measure the S parameters of the balun using a 2-port network analyzer. However for a low loss balun a back to back measurement of baluns of the same design allows a close approximation. In this case

$$S_{11}^{D} \approx S_{11} + S_{12}\,S_{21}S_{11}\big/\left(1 - S_{22}S_{11}\right)$$

$$\approx 2\,S_{11}$$

$$S_{11} \approx S_{11}^{D}\big/2$$

$$S_{12} \approx \sqrt{\left|S_{12}^{D}\right|}$$

Where S_{11}^{D} and S_{12}^{D} are the S parameters of the back to back connection from which the S parameters of the individual balun can be approximated. When the balun is connected to an antenna with S parameter S_{11}^{A} the S_{11} of the antenna connected to the antenna is given by

$$S_{11}^{B} = S_{11} + S_{12}S_{21}S_{11}^{A} \Big/ \left(1 - S_{22}S_{11}^{A}\right)$$

If the impedance of the ferrite is real with a value R then the model predicts

$$|S_{12}| \approx 1 \big/ \left(1 + 25/(2R)\right)$$

For a short 50 Ω transmission line. For R=600 Ω the loss is 0.18 dB.

B] Balun measurements

Two versions of the balun were measured. The first version was the current version using a single ferrite core on each "leg" of the balun. The second version was one with 2 cores per leg for a total of 4 cores per balun. Figures 2 and 3 show the back to back measurements of the small and large versions of the balun.

C] Noise model

An approximate noise model for the effect of the balun is given by

$$T_{out} = T_A\left(1 - |S_{11}|^2\right)L + T_{amb}\left(1 - L\right)$$

Where T_{out} is the noise temperature out of the balun, T_A is the antenna temperature, T_{amb} is the ambient temperature, S_{11} is the measured antenna reflection coefficient measured through the balun and L is the balun loss $\left(|S_{12}|^2\right)$. For a loss of 0.2 dB the added from the balun is about 30 K. A more accurate noise model can be obtained from the circuit model assuming the ferrites produce uncorrelated thermal noise from the resistive portion in their impedance.

Figure 4 shows the noise out of the balun for a constant antenna temperature of 1000 K using s11 from the FEKO modeled antenna impedance. On the coarse scale of the plot the approximate noise model and the circuit based noise model for the balun look very close but there is a difference which is critical to EDGES. The more complete model shows a dependence of the ambient noise contribution on the antenna impedance due to reflections of the thermal noise in the ferrite cores from the antenna. Figure 5 shows the difference of the curves in figure 4 on a finer scale. While it may still be possible to model this variation with enough accuracy to still detect an EoR signature of 100 mK it is clear that this has the potential to be the major systematic in EDGES. The effect is large enough that a 1% error in the determination of the balun loss results in a 300 mK systematic signature. This could be reduced with a balun of much lower loss, perhaps one with more cores or an entirely new approach.

D] Measurements with analyzer in differential mode

It would be useful to compare the results of the back-to-back measurements with measurements using a 4-port analyzer. A complication with using 2 ports of the analyzer in differential mode is that a correction is needed to change the impedance of these ports to 25Ω in post-processing code. Another complication is the need to use connectors and to correct for any added effects of the connectors. Also, at a minimum, a common plate needs to join the outer connections to the ports used in differential mode placing the balun in a metal box with bulkhead connectors might be a good way of solving this problem. It is also possible to use a 2-port analyzer to make multiport measurements 2-ports at a time with other ports terminated in 50Ω.

E] Comments

While the loss of the larger 4 cone balun of about 0.2 dB is better than the 2 cone balun the improvements is less than a factor of 2 especially at the higher frequencies. The increase in loss and degradation in match with increased frequency is largely the result of the added series inductance in the transition from the coax to the twin line terminals at the balanced end of the balun. Copper losses in the antenna will have an effect similar to the losses in the balun but the effects should be very small as copper loss in the antenna is estimated to be only about 0.002 dB (about 100 mK).

1] F.H. Raab, "Model for low-frequency performance of ferrite-loaded balun transformers," Microwave symposium, IEEE/MTT-S, 2007.

2] A. Fanti et al. "analysis of modeling of broad-band ferrite-based coaxial transmission-line transformers," Proc. 40th European Microwave Conference, Paris, 2010.

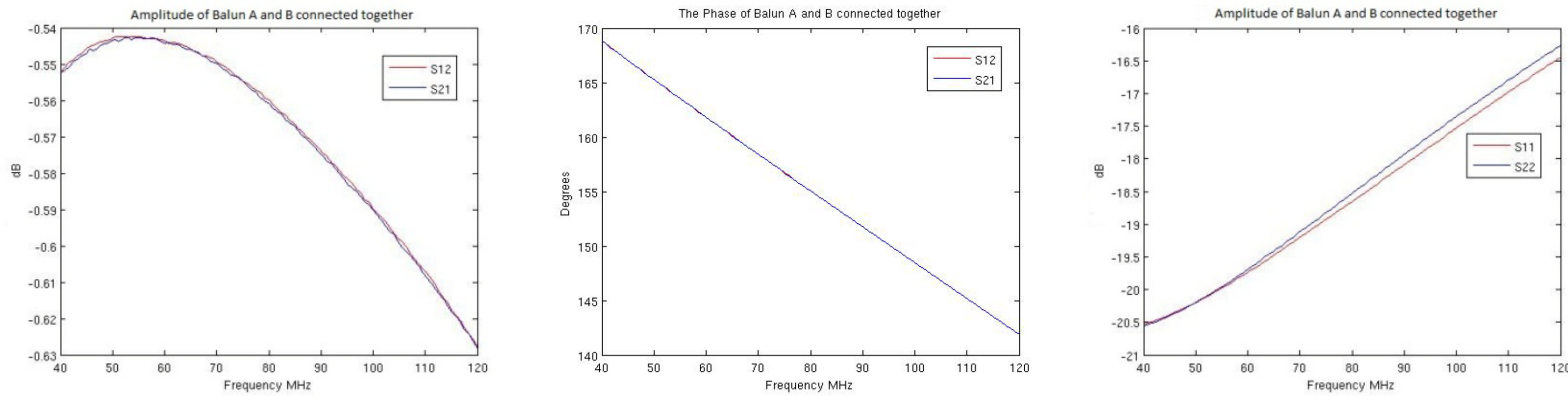

Figure 2. S parameters of single ferrite core/leg balun.

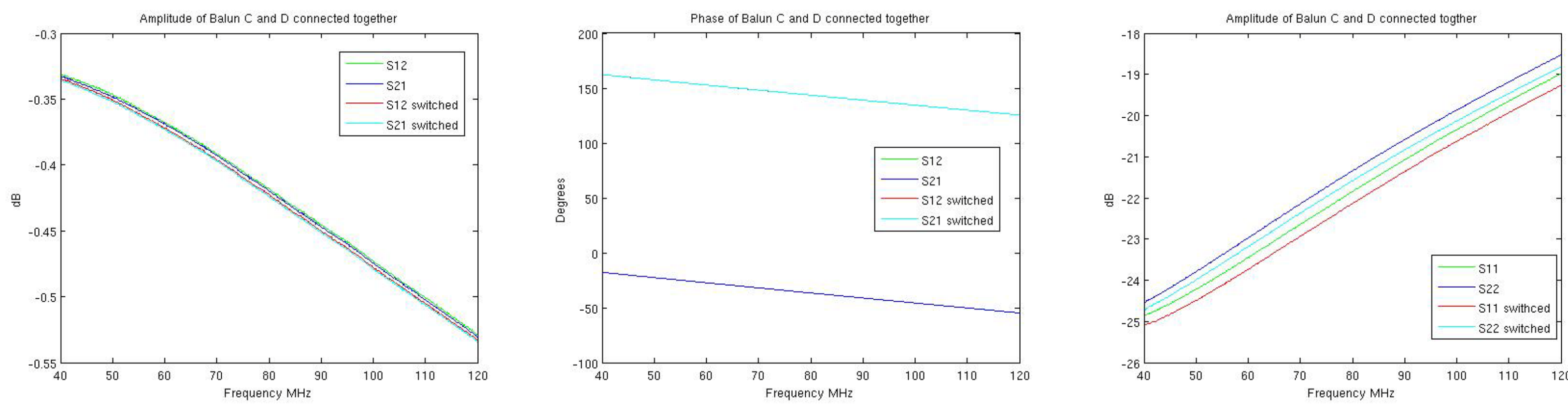

Figure 3. S parameters of 2 core/leg balun.

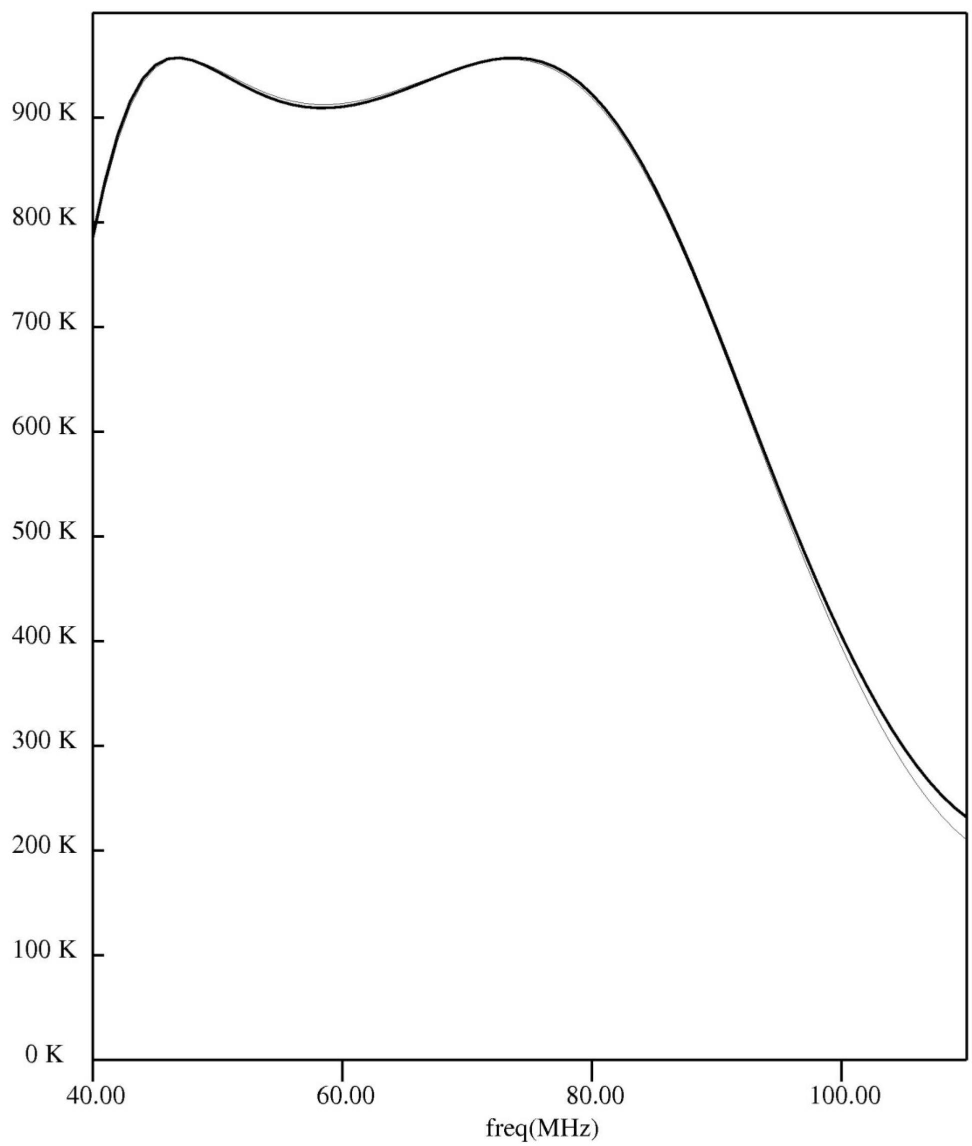

Figure 4. Output temperature of balun connected to antenna in uniform 1000 K sky for 2 models of balan noise. The difference is shown in Figure 5.

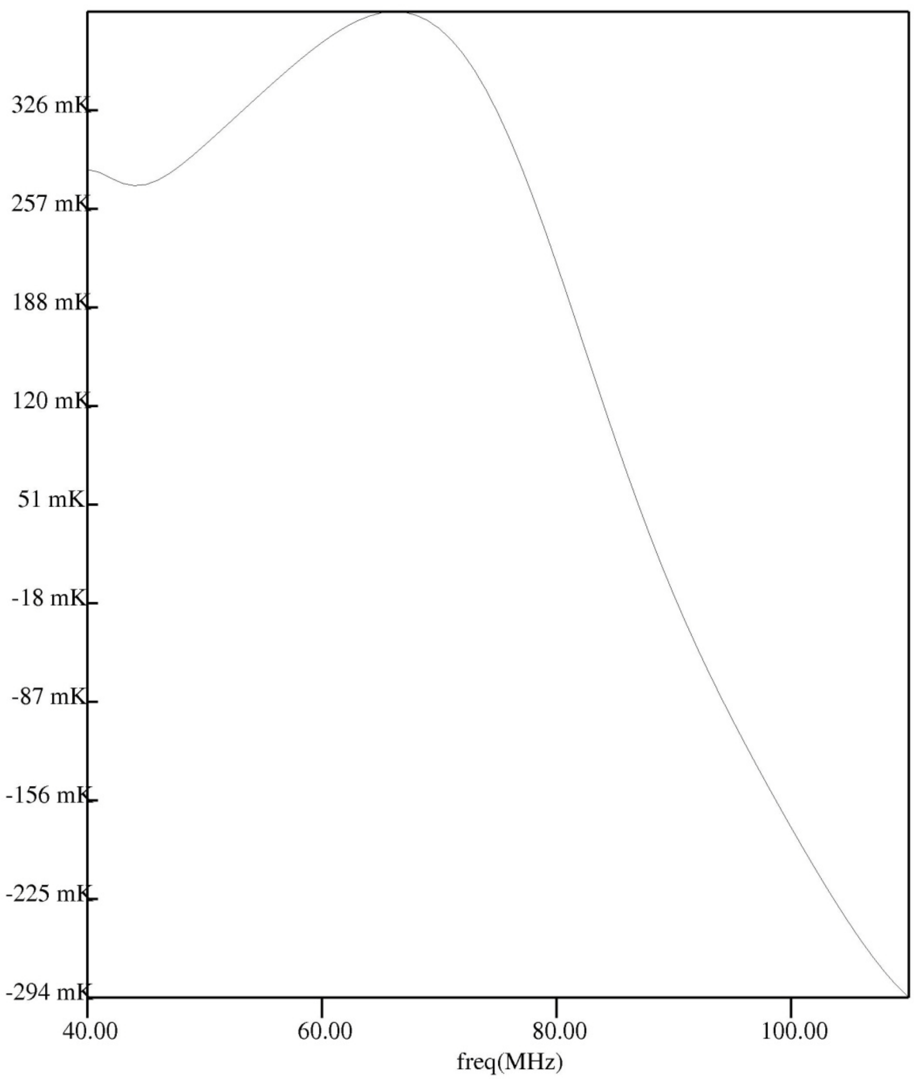

Figure 5. Difference between an approximate noise model which assumes balun only introduces a loss and a more accurate model which includes the effects of mismatch.