AN2501 - Ka-Band Vector S_{21} Measurement with EECL's Dual Frequency Extender and Low-Cost VNA

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Introduction

A key use case for EECL's Dual Frequency Extender is to extend low-frequency test equipment up to 32 GHz (Ka-band). A lower-cost low-frequency Vector Network Analyzer (VNA), such as the LA Techniques LA19-13-04B which operates natively up to 8.5 GHz can be used in conjunction with the Dual Frequency Extender to obtain *vector* (magnitude and phase) S_{21} measurements up to 32 GHz. Such a system offers significant cost reduction compared to a commercial Ka-Band capable VNA, while maintaining accuracy sufficient for most practical measurements.

This application note presents the methodology for obtaining and calibrating S_{21} measurements using this approach in section 1, and compares the accuracy of such measurements against a commercial Keysight 44 GHz VNA in section 2. A brief discussion on long-term calibration stability considerations is presented in section 3.

1 Measurement Setup and Calibration

1.1 Measurement Setup and Frequency Planning

For the purposes of VNA frequency extension for S_{21} measurements, the setup of the Dual Frequency Extender is shown in fig. 1. The low-cost VNA ports are connected to the Dual Frequency Extender's IF ports, and the Device Under Test (DUT) is connected to the RF ports.

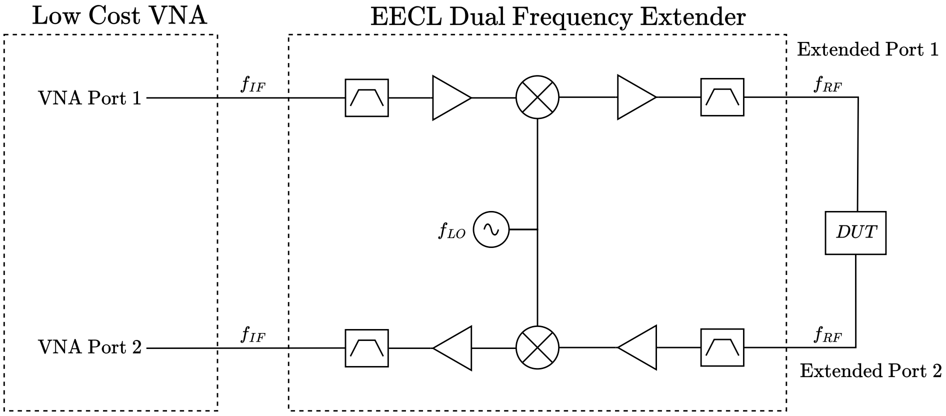


Figure 1: EECL Dual Frequency Extender Setup for VNA frequency extension

The VNA source frequency f_{IF} is up-converted to f_{RF} forming the Extended Port 1. After passing through the DUT, it arrives at Extended Port 2, where it is subsequently down-converted back to f_{IF} for detection at the VNA receivers. Note that the block diagram displayed is greatly simplified compared to the true internal hardware of the Dual Frequency Extender.

The frequency planning (selecting a suitable LO frequency f_{LO}) is key to a successful measurement and calibration. The Dual Frequency Extender hardware supports both high-side and low-side LO mixing, however the image reject filters on the RF and IF sides are optimized only for one of the two configurations (varying by RF frequency). Please consult EECL directly for documentation on frequency planning with the Dual Frequency Extender.

As an example, consider making an S_{21} measurement of a DUT in the range from 25 GHz to 29 GHz, using a VNA natively capable of reaching only 8.5 GHz. For this example, consider low-side LO mixing, such that the extended port frequency f_{RF} is

$$f_{RF} = f_{LO} \pm f_{IF} \tag{1}$$

The larger frequency $f_{LO} + f_{IF}$ will be the desired output tone, while the lower $f_{LO} - f_{IF}$ is an unwanted mixing image. Thus the built-in image reject filters in the Dual Frequency Extender are set to remove this image. Based on this setup, we can choose an LO frequency of $f_{LO} = 22$ GHz, such that a measurement taken at the VNA in the range 3 GHz to 7 GHz, corresponds to the desired Extended ports from 25 GHz to 29 GHz. This is the exact frequency plan and setup used in the example measurements presented in section 2.

1.2 Calibration Methodology

As with any VNA measurement, the measurement calibration (vector error correction) methodology is of great importance to the accuracy of the final result. In an ideal case, a full 2-port calibration (SOLT, TRL or similar) would be obtained, similar to any normal VNA measurement. However, without the addition of an external coupler and dedicated switches, the Dual Frequency Extender cannot be used to obtain reflection measurements (S_{11}, S_{22}), thus a full 2-port calibration method cannot be used.

Instead, the transmission normalization method, also known as the response thru calibration method, can be used, involving the measurement of a single calibration standard - a *known* thru.

The mathematical implemention of the transmission normalization algorithm, is as follows. A simplified diagram of the measurement setup can be seen in fig. 2.

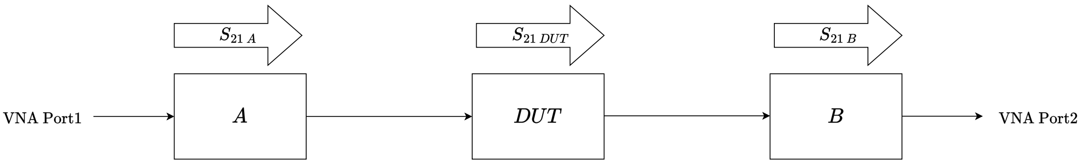


Figure 2: Simplified Flow Diagram of DUT measurement

Black box A is seen to include the frequency upconversion fixture, including the dual frequency extender hardware and cabling to the device under test. Similarly, black box B is seen to include the frequency downconversion fixture, including the dual frequency extender hardware and cabling from the device under test. Note that, mathematically, the fact that fixtures A and B include frequency conversion can be ignored for the purposes of calibration, provided that it is understood that the final calibrated S_{21} measurement is representative of the device response at the up-converted frequency f_{RF} and not the native VNA frequency f_{IF}.

Assuming a perfect impedance match throughout the system (i.e. $S_{11} = S_{22} = 0$ at all interfaces), the measured overall S_{21} parameter between VNA ports 1 and 2 will be:

$$S_{21,M} = S_{21,A} \times S_{21,DUT} \times S_{21,B} \tag{2}$$

Note that each each s-parameter S_{21} is seen a complex number, and a function of frequency, thus including both magnitude and phase information over the measurement band:

$$S_{21} = A(\omega) \times e^{j\phi(\omega)} \tag{3}$$

In general, however, a perfect impedance match cannot be assumed, and some reflections will occur in the system, for example as shown in fig. 3 In this case the overall measured S_{21} will involve a summed term in the form $S_{11,DUT} \times S_{22,A} \times S_{21,DUT} \times S_{21,B}$, and similarly for other reflective loops. Provided that a good, but not perfect match is present, these terms have very small contribution to the overall magnitude and phase, since they include a product of two return loss values. Such errors due to imperfect matching can be observed as riples in the magnitude and the phase of the final S_{21} measurement, however they are typically small and do not impact the overall shape of the response. Thus for the purposes of this application note, eq. (2) can be taken to hold as is.

To obtain the measurements of the S_{21} of just the device under test, it is clear that the measured $S_{21,M}$ from eq. (2), must be divided by $S_{21,A} \times S_{21,B}$. To obtain this value, two options are available. Firstly, if the connectors to the DUT are opposite genders, they can be directly connected together

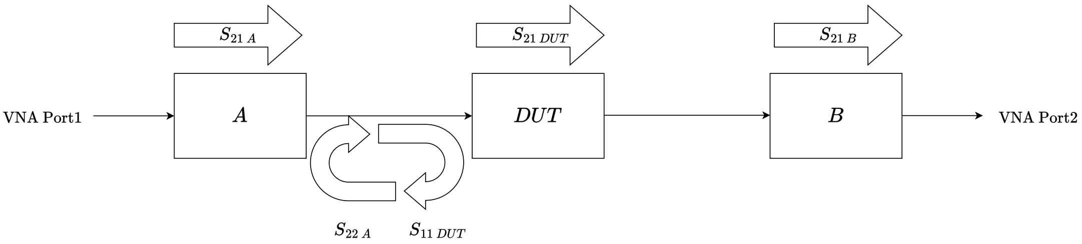


Figure 3: Simplified Flow Diagram of DUT measurement with mismatch error

and a calibration measurement taken. This approach is typically refered to as a zero-length (or insertable) thru in the literature and is shown in fig. 4.

Figure 4: Simplified Flow Diagram of Zero-Length Thru calibration measurement

In this case the calibration standard measurement is simply

$$S_{21,CAL} = S_{21,A} \times S_{21,B} \tag{4}$$

and the DUT S-parameter can be extracted from the uncalibrated measurement in eq. (2) simply by direct division:

$$S_{21,DUT} = \frac{S_{21,M}}{S_{21,CAL}} \tag{5}$$

More often that not, however, the connectors to the DUT will be the same gender, thus a zero-length thru aproach cannot be used. Instead a physical (non-insertable) thru standard, typically a short-length male-to-male or female-to-female adapter can be used, whose S_{21} s-parameter must be known (both magnitude and phase). The S_{21} parameter of such a thru standard is typically obtained by direct measurement at the final measurement frequency by a calibrated VNA.

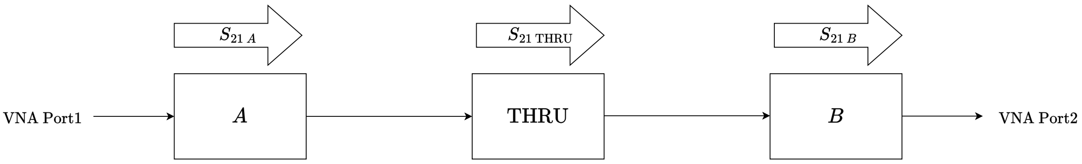


Figure 5: Simplified Flow Diagram of Known Thru calibration measurement

In this case, the calibration standard measurement S_{21} becomes

$$S_{21,CAL} = S_{21,A} \times S_{21,THRU} \times S_{21,B} \tag{6}$$

The DUT S_{21} can then be extracted from the uncalibrated measurement in eq. (2) as

$$S_{21,DUT} = S_{21,M} \times \frac{S_{21,THRU}}{S_{21,CAL}} \tag{7}$$

noting once again, that $S_{21,THRU}$ must be known, and can be therefore directly substituted into the above equation.

An implementation of the calibration methodology as described above is available by request from EECL in both Python and Matlab, and is integrated into EECL's existing Matlab Automated Test Suite.

On request, EECL can also provide thru standards with SMA or 2.92 mm connectors, along with their measured response for calibration.

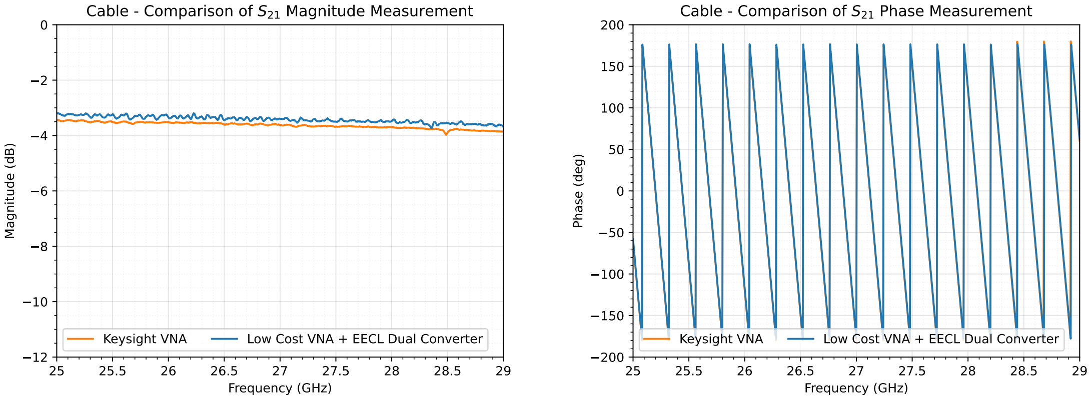
2 Comparison with Keysight 44GHz VNA

The accuracy of the measurement and calibration methodology described above can be verified by direct comparison with reference measurements from a commercial Vector Network Analyzer capable of measuring at Ka-Band. For this application note, the reference VNA is a Keysight P5007A, capable of measurements up to 44 GHz. The measurement setup using the EECL Dual Frequency Extender is as shown in fig. 1, and uses the LA Techniques LA19-13-04B as the low-cost VNA to be frequency extended. The frequency planning is as discussed in the example in section 1.1.

Two devices were characterized independently in the frequency range from 25 GHz to 29 GHz. The first device is a 1 m coaxial cable with 2.92 mm connectors, with a relatively flat magnitude and phase response. The second device offers a more complex S_{21} behavior as a demonstration of more practical measurements, such as an antenna pattern determination.

2.1 2.92 mm Coaxial Cable Measurement

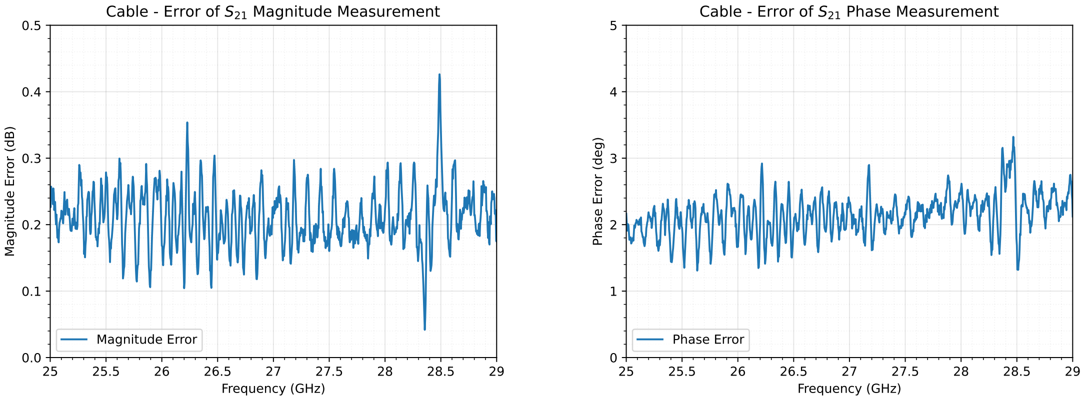
The measured magnitude and phase of S_{21} of the coaxial cable can be seen in fig. 6. Overall good agreement can be seen between the measurements taken with the dual frequency extender, and the reference values from the Keysight VNA. The respective magnitude and phase errors are shown in fig. 7.



(a) S_{21} magnitude (dB)

(b) S_{21} phase (deg)

Figure 6: Coaxial Cable S_{21} Measurement



(a) S_{21} magnitude error (dB)

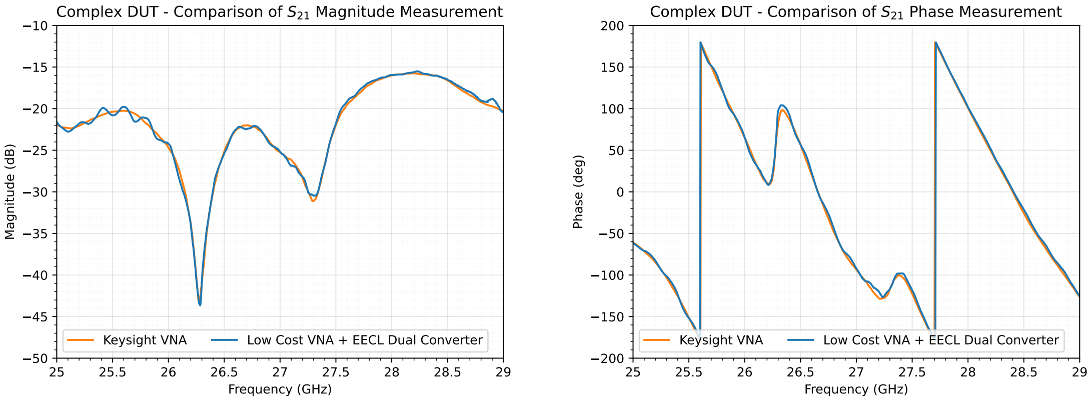
(b) S_{21} phase error (deg)

Figure 7: Coaxial Cable S_{21} Measurement Error

The magnitude error is below 0.5 dB at worst, and is below 0.3 dB over the majority of the frequency band. The phase error is slightly over 3° at its worst case, and is below 2.5° for the majority of the measured band. This level of accuracy is more than sufficient for many practical measurements.

2.2 Complex DUT Measurement

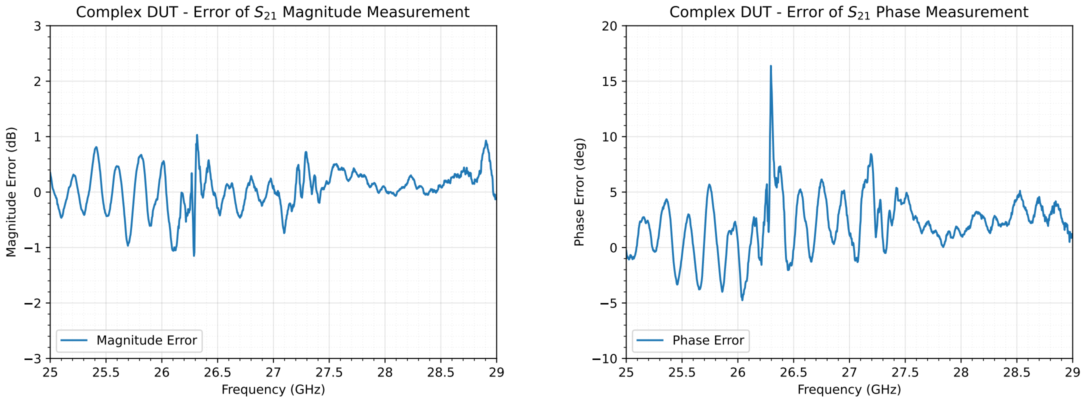
The measured S_{21} of the complex DUT can be seen in fig. 8. Again good agreement can be observed between the frequency extended VNA, and the reference instrument. The respective magnitude and phase errors are shown in fig. 9.



(a) S_{21} magnitude (dB)

(b) S_{21} phase (deg)

Figure 8: Complex DUT S_{21} Measurement



(a) S_{21} magnitude error (dB)

(b) S_{21} phase error (deg)

Figure 9: Complex DUT S_{21} Error

The worst-case magnitude error is around ±1 dB. The phase error is slightly over 15° at its worst case, and is below ±5° for the majority of the measured band. Again, this level of achieved accuracy is more than sufficient for a wide range of practical S_{21} measurement applications. The observed ripple in S_{21} magnitude and phase is due to small impedance mismatches in the system, leading to a loss of accuracy in the normalization calibration algorithm (the mathematics for which assumes $S_{11} = S_{22} = 0$ at every interface, as described in section 1.2). In cases that such a ripple is too large to be acceptable, certain techniques can be used to mitigate mismatch effects, such as adding well-matched attenuators at mismatched junctions. If the mismatch can be externally characterized, mathematical extensions of the normalization calibration algorithm can be used to compensate the mismatch error.

3 Long-Term Calibration Stability

EECL's Dual Frequency Extender includes built-in heater-based temperature stabilization, as well as a low-drift reference oscillator from which the LO frequency is derived. Thus, if configured correctly, the extender exhibits virtually no drift, even over long-term measurements.

Subsequently, once a calibration is obtained it can be used over multiple measurements and over long time periods, without having to redo the thru calibration standard measurement. The calibration is also valid after a full power cycle of the dual frequency extender, due to the shared LO nature of the frequency conversion. Note that after a power cycle, the calibration becomes valid only after the dual frequency extender reaches its temperature set point. Nevertheless, EECL recommends that the calibration measurement is redone occasionally, for example on a weekly basis, to offset and compensate any small drift or error.

Note that many low-cost VNAs are not temperature-stabilized, and thus will introduce measurement drift at a rate much higher than the Dual Frequency Extender. In cases where such drift is present in the VNA, it determines the rate at which calibration measurements must be retaken.

4 Conclusion

This application note has presented a measurement setup and calibration methodology for obtaining vector (magnitude and phase) S_{21} measurements up to Ka-Band using the EECL Dual Frequency Extender and a low-cost low-frequency VNA. Measurements were obtained using this setup, and their accuracy was compared to a reference 44 GHz Keysight VNA.

The proposed measurement setup displayed good agreement with the reference VNA for both magnitude and phase of S_{21}, while offering significant cost reduction.