THz Vector Network Analyzer Measurements and Calibration

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***Abstract*— Virginia Diodes is developing a series of Vector Network Analyzer extenders to cover waveguide bands from WR-10 (75-110 GHz) up to WR-1.0 (750-1100 GHz). This article discusses the basic configuration of the VDI extenders, and shows examples of several systems. Several measurement examples are discussed, including the measurement of waveguide loss, interface mismatch, and loads. Initial measurements of a WR-1.2 (600-900 GHz) extender are presented, showing a typical dynamic range of 85 dB.**

I. Introduction

Vector Network Analyzers (VNAs) are used to accurately measure the complex scattering parameters for a wide variety of devices in different environments, and are a key measurement instrument in the microwave and millimeter-wave frequency ranges. The accuracy of the VNA is achieved by using high quality signal sources and receivers, as well as sophisticated calibration methods that have been developed to eliminate systematic errors.

Virginia Diodes (VDI) is developing a series of modules that can be used to extend the frequency range of modern VNAs up to THz frequencies. This article describes the basic layout and operation of these VNA Extenders. In addition, measurements of waveguide components in the WR-1.5 (500-750 GHz) band are presented.

II. Frequency Extender Configuration

A schematic of VDI's frequency extender configuration is shown in Fig. 1. The extender consists of a transmitter followed by back-to-back directional couplers. A receiver is attached to each of the couplers; one to sample the outgoing signal (i.e. the Reference Mixer) and one for the incoming/returning signal (i.e. the Measurement Mixer). The two VNA drive signals (one for the transmitter and one for the receivers) are offset by a fixed amount to generate IF signals at a constant frequency, which are then measured by the VNA.

The transmitter consists of an amplifier followed by a series of full waveguide band frequency multipliers. Back-to-back directional couplers at the transmitter output are used to route the signal power. One coupler samples the outgoing power and the second samples the input power that is received from the test port. This input power may be either a signal transmitted by this module and reflected off of the device under test (S11) or a signal transmitted by a separate module through the DUT (S21, for example). Each receiver consists of an amplifier and multipliers that generate the LO

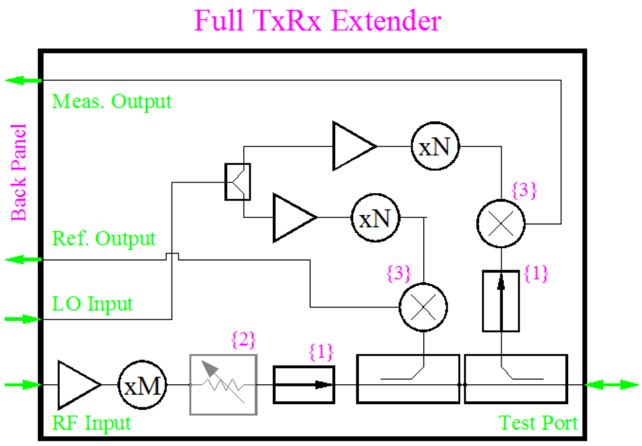


Fig. 1. VDI TxRx frequency extender configuration.

drive power and finally a subharmonic mixer, which gives high sensitivity and suppresses LO noise. The Reference mixer sets the amplitude and phase reference for the system, and the Measurement signal provides information about the Device Under Test (DUT).

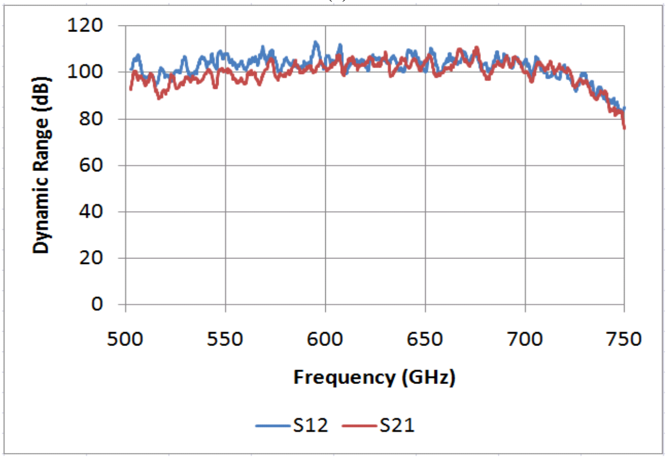
For full two-port measurements (i.e. measurement of all four S-parameters) two TxRx Extenders are used. For one-path two-port measurements (i.e. measurement of S11 and S21 only), one TxRx Extender and one Rx Extender (consisting of a single receiver) can be used.

III. WR-1.5 (500-750 GHz) Measurements

A pair of VNA Extenders to WR-1.5 (500-750 GHz) are shown in Fig. 2. The multipliers and mixers in the extenders rely on VDI's series of full waveguide band THz Schottky diode components, e.g. doublers, triplers, and subharmonic mixers. These components produce high output power and low conversion loss, yielding state-of-the-art sensitivity and bandwidth for the extenders. In addition to these components, a full line of directional couplers and other waveguide components have been developed. The WR-1.5 extenders have an average dynamic range of 100 dB (with 10 Hz bandwidth), and a test port power of -25 dBm (typ.).

For calibration a TRL method was used, with a flush connection for the Thru, a ¼ wave delay for the Line, and short circuits for the Reflects. Measurements of the full two-

(a)



(b)

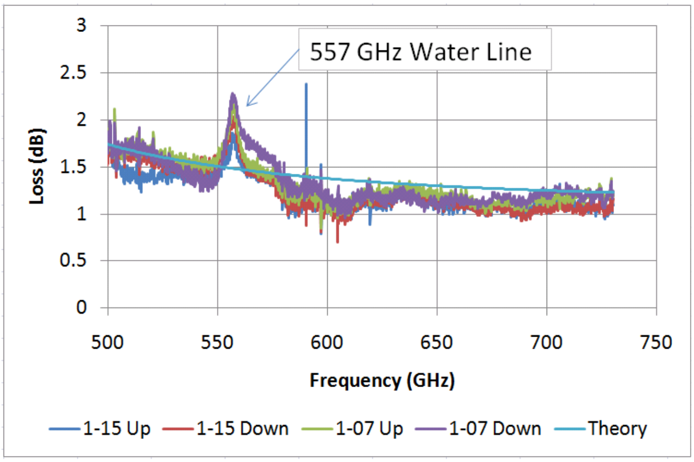
Fig. 2. (a) Photograph and (b) measured dynamic range of a WR-1.5 VNA Extender.

port S-parameters were performed using a pair of TxRx heads.

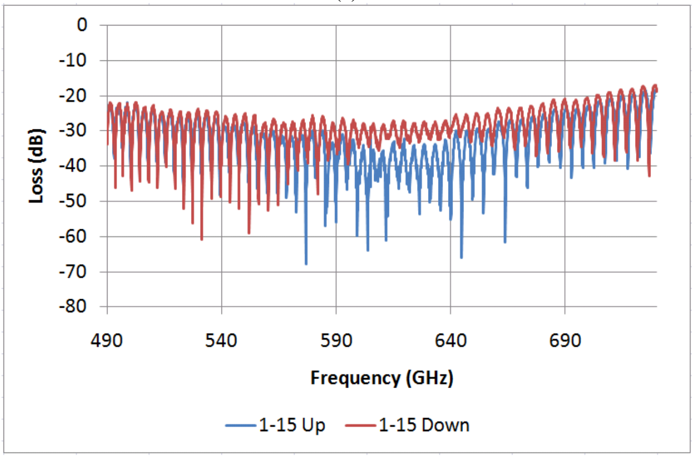
Fig. 3 shows measurements of a 25 mm long section of straight WR-1.5 waveguide. The return loss is dominated by reflections from the waveguide interface at each end, which introduces standing waves in the S21 measurement. The reflections from the two interfaces can be seen clearly in the time-domain data, shown in Fig. 4. The measured waveguide loss (Fig. 3(a)) matches the calculated loss of smooth-walled gold-plated waveguide, indicating the quality of the machining and gold. Similar loss measurements at other submillimeter bands have found that the loss for VDI waveguide ranges from 1-1.5 times the theoretical limit. The measurement disturbance at 557 GHz is caused by the strong water line at that frequency.

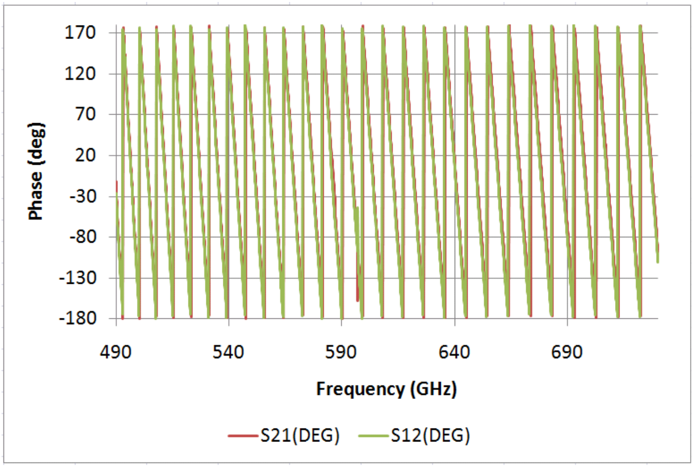
Fig. 5 shows a measurement of the loss of a 90 degree H-plane bend (length ~ 20.7 mm). The loss for this waveguide is about 5 times the calculated "ideal" loss. The dominant reason for the high loss is that the waveguide (made in two pieces) is split in the H-plane. The waveguide measured in Fig. 3 was split in the E-plane, which has less loss because there are no currents crossing the split.

Fig. 6 shows the return loss of a WR-1.5 waveguide load in both the frequency and time-domain. The ripples in the return loss measurement (Fig. 6(a)) are caused by reflections between the waveguide interface and the waveguide termination. The return loss of the interface mismatch and of the termination are seen to be comparable.



(a)





(c)

Fig. 3. (a) Insertion loss, (b) Return loss, and (c) transmission phase for a 25 mm long straight waveguide section. The standing wave pattern is reflections from the waveguide interface at each end of the block. The notation "up" and "down" refers to the waveguide orientation of the UG-387/U-M flange, which can be re-connected after a rotation of 180 degrees. Ideally the curves for "up" and "down" should be identical, and differences indicate alignment issues between the waveguide and the alignment dowels.

IV. WR-1.2 (600-900 GHz) Development

Work is underway to develop extenders to above 1 THz. As an example, the dynamic range of a WR-1.2 prototype is shown in Fig. 7. A non-optimal drive chain was used for this measurement, and so the system frequency range is shifted

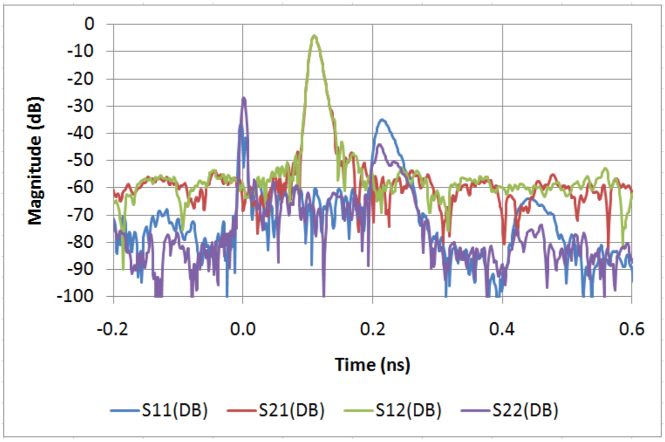


Fig. 4. Time domain measurement of a 25 mm long section of WR-1.5 straight waveguide

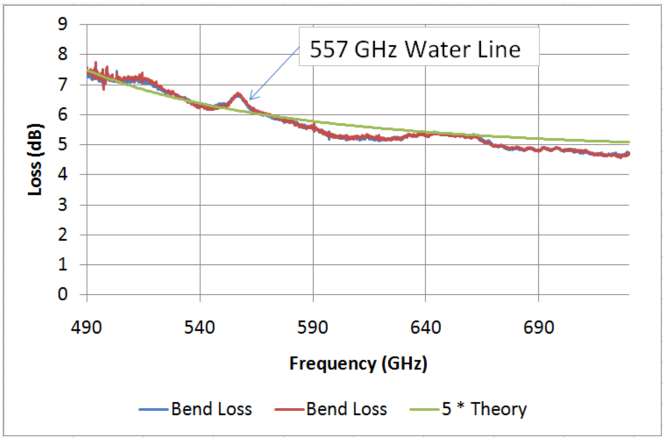


Fig. 5. Insertion loss for an H-plane bend, length ~ 20.7 mm.

higher in the waveguide band. Even so, this extender demonstrates excellent dynamic range up to 950 GHz. Work is underway to develop a drive chain that better matches the standard WR-1.2 waveguide band. Calibration standards have also been successfully developed for this band, and calibrated measurements will be performed once the system has been optimized. A WR1.0 system (750-1,100GHz) is also under active development.

V. Conclusions

Frequency extenders with high dynamic range have been developed up to 750 GHz, and research is underway to develop calibrated VNA measurements up to 1,100 GHz. Initial measurements have demonstrated dynamic range of 85 dB (typ.) up to 950 GHz. These extenders have excellent amplitude and phase stability, and can be used to perform accurate measurements up to THz frequencies.

VI. Acknowledgements

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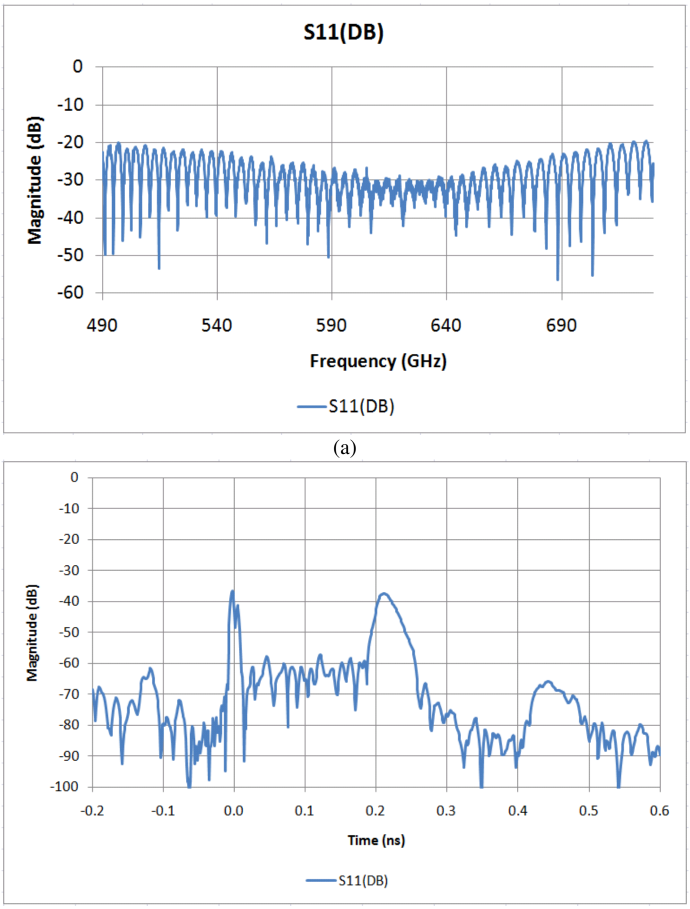

(a)

(b)

Fig. 6. S11 measurements of waveguide load.

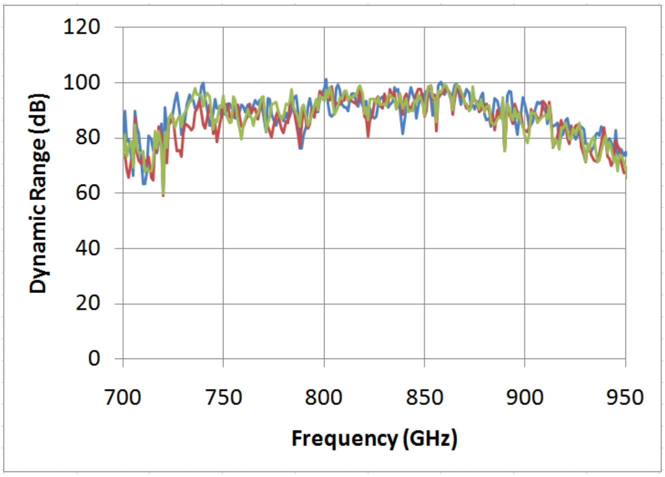

Fig. 7. Measured dynamic range of a WR-1.2 VNA Extender.