Frequency Extenders for 75 – 1,100GHz

Thomas W. Crowe, Jeffrey L. Hesler
Virginia Diodes, Inc.
979 Second Street SE
Charlottesville, VA 22902, USA

***Abstract*- Virginia Diodes is developing a series of frequency extenders for operation in the waveguide bands spanning from WR10 (75-110GHz) through WR1.0 (750-1,100GHz). These will include extenders for sources, spectrum analyzers and vector network analyzers. This paper reviews the progress of this development, with emphasis on the VNA extenders for the highest frequency bands, including results up to 1.1THz.**

I. Introduction

Vector Network Analyzers (VNAs) are a primary piece of test and measurement equipment in all modern microwave and mm-wave laboratories. VNAs can be used to accurately measure the complex scattering parameters for a wide variety of materials and devices. The accuracy of the VNAs is due to the high quality of its components and sophisticated calibration methods that have been developed to eliminate systematic errors. The flexibility and accuracy of the instrument make the VNA invaluable for the testing and development of components and systems.

Virginia Diodes (VDI) has developed 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 and recent results in the WR1.0 band are presented.

A. VNA Extender Configuration

The frequency extender consists of a set of frequency multipliers and mixers that are used to convert the test signal from the VNA (typically below 50 GHz) up to THz frequencies, and then mix the return signals from the sample under test back down to the IF bands used by the VNA receivers. A basic 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 transmitter and receivers are driven by two independent synthesized signals from the VNA. The VNA's drive signals are offset by a controlled amount as the frequency is swept, so as to maintain a constant IF frequency, which is then sampled by the VNA.

The transmitter consists of an amplifier followed by a series of full waveguide band frequency multipliers. Each receiver consists of an amplifier, multipliers and mixer. VDI uses subharmonically-pumped mixers, which yield high sensitivity and suppress LO noise. The Reference mixer measures the amplitude and phase reference for the system, and the Measurement mixer acquires information about the Device Under Test (DUT).

For full two-port measurements (i.e. simultaneous measurement of all four S-parameters) two TxRx Extenders are required. Whereas 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.

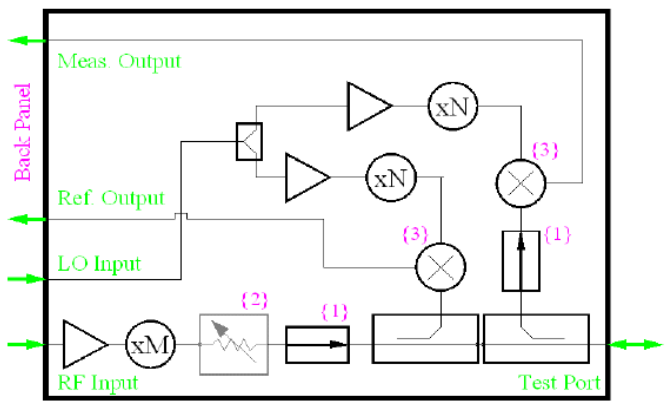


Fig. 1: The basic block diagram of the standard VDI VNA extender head (TxRx).

B. WR1.5 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 full waveguide band THz Schottky diode components, e.g. doublers, triplers, and subharmonic mixers. These components produce high transmitter power and excellent receiver sensitivity. For example, the WR-1.5 extenders have a typical dynamic range of 100 dB (with 10 Hz resolution bandwidth).

For calibration, a TRL method is often used; with a flush connection for the Through, short circuits for the Reflect and a ¼ wave delay for the Line. 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 of the waveguide and the electroplated gold. Similar loss measurements at other submillimeter bands have shown that the loss for VDI

waveguide ranges from 1-1.5 times the ideal level expected. The measurement disturbance at 557 GHz is caused by the strong water line at that frequency.

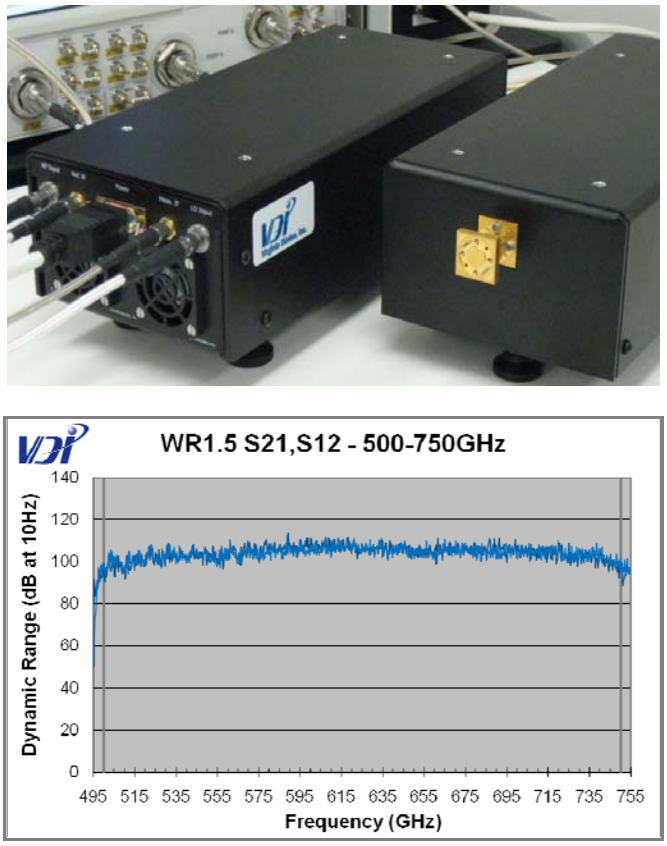


Fig. 2: A pair of WR1.5 extender heads (TxRx and the measured dynamic range (RBW=10Hz).

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 this waveguide component (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 internal termination are seen to be comparable.

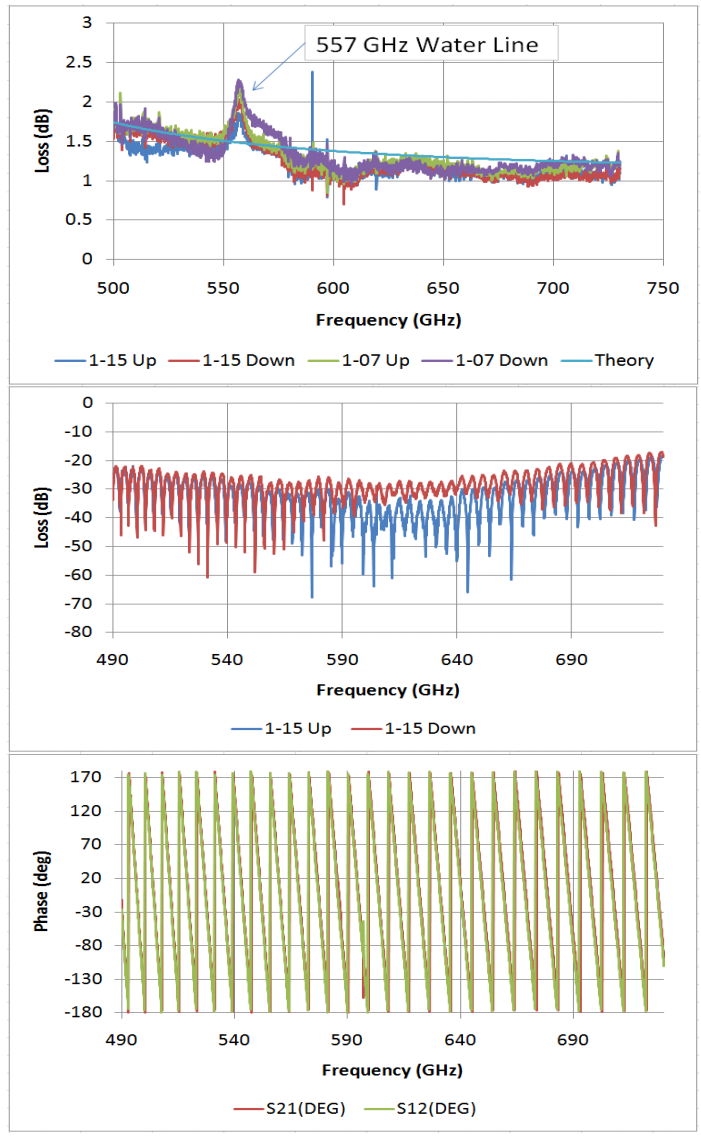


Fig. 3: (a) Insertion loss, (b) Return loss, and (c) transmission phase for a 25 mm long straight waveguide section. The notation "up" and "down" refers to the waveguide orientation of the UG-387/U-M flange, which can be re-connected after a rotation of 180 degrees.

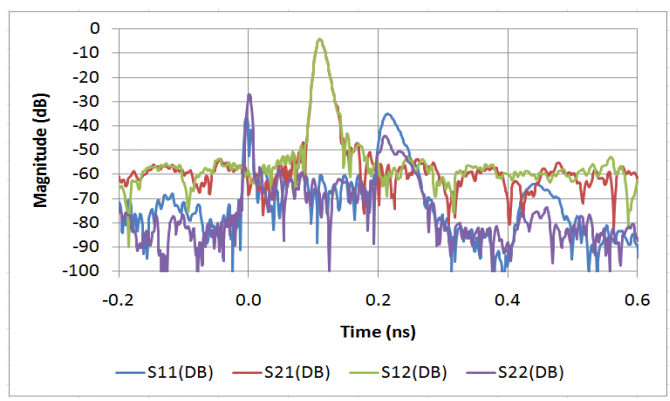


Fig. 4: Time domain measurement of a 25 mm long section of WR-1.5 straight waveguide.

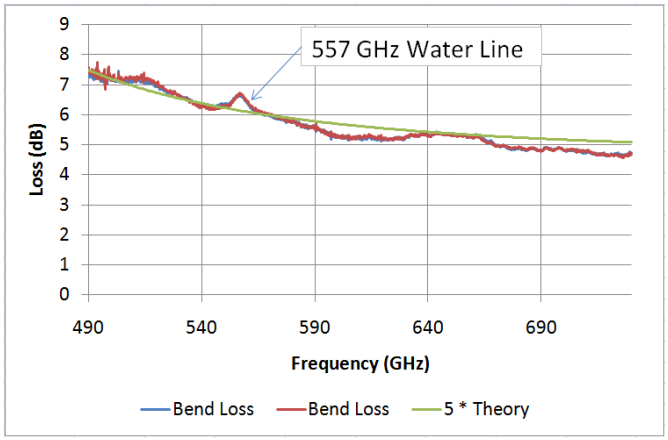
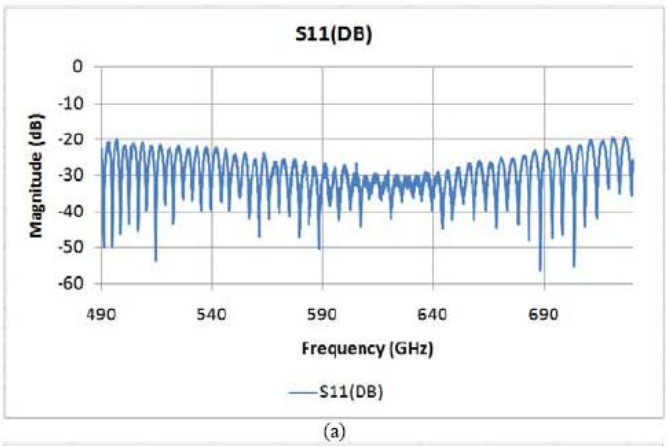
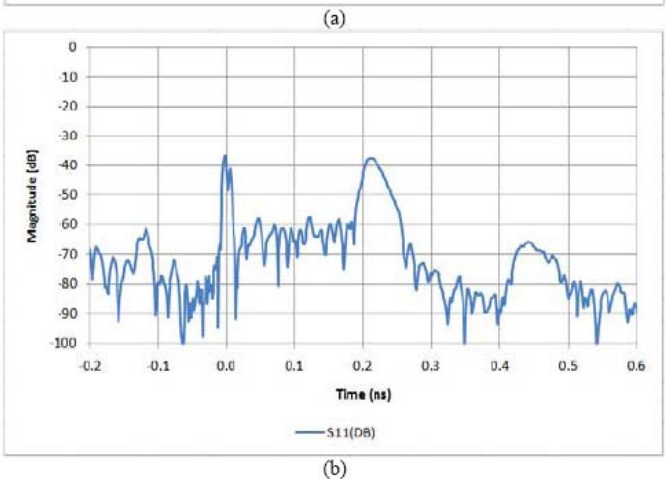


Fig. 5: Insertion loss for an H-plane bend, length ~ 20.7 mm.



(a)



(b)

Fig. 6: (a) The magnitude of S11 for a matched load and (b) time domain measurement for the same component.

C. Initial Results at WR1.0 (750- 1,100GHz)

Given the success at WR1.5, it was decided to develop a similar set of extenders for the WR1.0 waveguide band. The packaging of the WR1.0 heads is identical to that used at WR1.5, and thus the heads are identical in appearance to those shown in Fig. 2. As shown in Fig. 7, a measured dynamic range of 50-70dB is achieved across almost the entire band, but with some significant roll-off below 800GHz. The overall degradation, compared to WR1.5, is caused by many factors. These include the reduced signal power available from the transmitter, the lower sensitivity of the receivers and increased losses in the directional couplers and other passive components. The roll-off below 80GHz is due to a particular frequency multiplier in the system, which will be improved in the next design. The performance above 1,000GHz will also be improved.

The magnitude and phase stability over a one hour period are depicted in Fig. 8. The stability below 800GHz will naturally improve when the system dynamic range is increased. Overall, the system shows reasonable stability in the part of the band where the dynamic range is high.

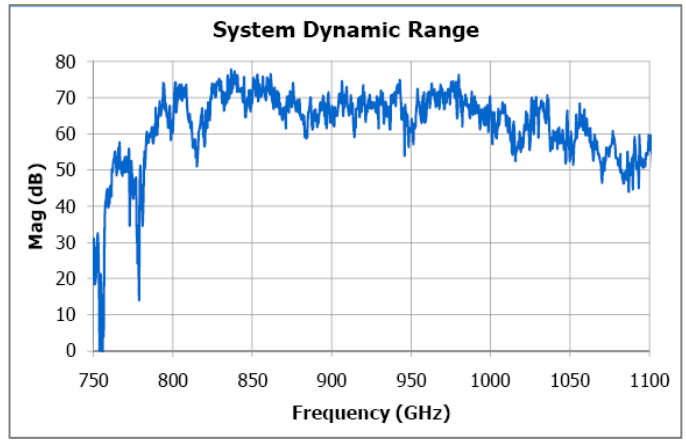


Fig. 7: The measured dynamic range of the first WR1.0 VNA frequency extender heads (RBW=10Hz).

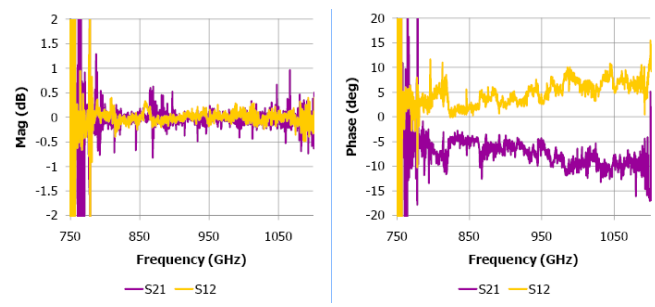


Fig. 8: The measured magnitude and phase stability of the WR1.0 system over one hour in an uncontrolled lab environment.

D. Optimizing Performance for Specific Applications

For some applications it can be beneficial to redesign the extender system to achieve specific measurement goals. For example, in the case of an antenna test range only one transmitter is normally required, and measurements of reflected power are generally not required. Further, given the large losses involved in the typical test range, any effort to increase the measurement dynamic range is worthwhile. VDI has recently developed and delivered a WR10 extender set for such an application. In this case the first extender consists of only a transmitter and reference receiver. The second extender

is a simple measurement receiver. This simplification increases the dynamic range, primarily because of the reduction in the number of lossy passive components in the signal path.

Also, in the case where the loss of the sample under test (in this case the range) is always large, receiver saturation is no longer a factor in the system design. Thus, the system dynamic range is often limited by the noise floor of the receivers and the available test port power. In this case, increasing transmitter power can yield significantly improved performance.

Fig. 9 shows the measured "effective" dynamic range of the WR10 system, showing a typical value of 150dB across the band. These measurements were taken with a variable waveguide attenuator between the two extender heads to simulate the range losses. The "effective" dynamic range is defined here as the measured dynamic range plus the amount of loss inserted. Perhaps a more appropriate method of stating the performance is that the system is able to achieve 125dB dynamic range even after overcoming a range loss of 25dB.

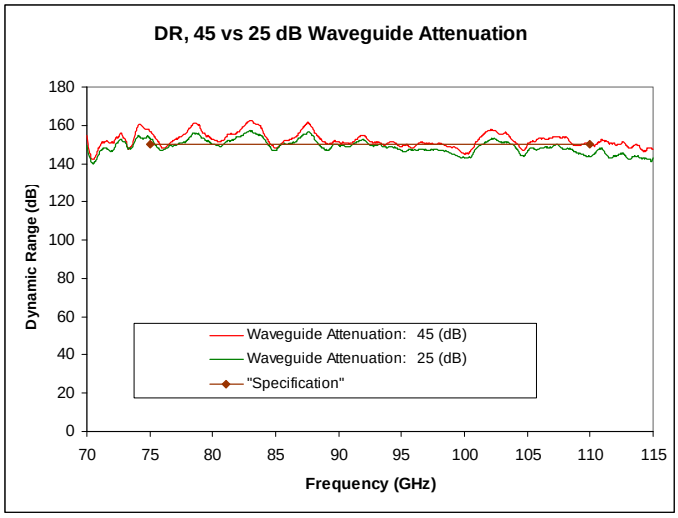


Fig. 9: The performance of a WR10 extender system that has been optimized for antenna test range measurements.

II. Discussion and Conclusion

Scientific fields, such as radio astronomy, chemical spectroscopy and plasma diagnostics, have long supported the development of sources and detectors of higher frequency radio waves. Over the last several decades these fields have pushed the development of more powerful sources and more sensitive receivers for use above 100GHz. This technology can now be used to produce test and measurement equipment with excellent performance at frequencies up to at least 1,100GHz. This paper has reviewed the performance of recently developed frequency extenders for Vector Network Analyzers. However, the same technology can also be used to extend the operation of other test and measurement equipment. For example, the transmitters in the VNA extenders can be used to extend millimeter wave synthesizers. In fact, full waveguide band performance can be achieved in all common bands up to 1.1 THz, and systems with narrower tuning band have been demonstrated up to at least 2.7 THz.

The basic receiver system used in the VNA extenders can be used as a high quality extender for a modern spectrum analyzer. For example, in collaboration with Agilent Technologies, VDI has recently demonstrated excellent performance to 750GHz with a VDI WR1.5 extender and the recently announced Agilent PXA Signal Analyzer [1].

The development of terahertz technology for scientific applications has led to a host of components and subsystems that are now useful for many other applications. A particularly important application is the development of high quality test and measurement equipment for this frequency band. This paper has reviewed the extension of Vector Network Analyzers to frequencies as high as 1.1THz. The same technology can also be used to similarly extent frequency synthesizers and signal analyzers. The availability of this new equipment should lead to a greater understanding of the properties and performance of terahertz materials, components and systems, and eventually to the developments of systems with far superior performance.

Acknowledgment

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References

[1] PXA Signal Analyzer: Agilent Technologies Announces the Industry's Highest Performance Millimeter-Wave Signal Analyzer, Agilent Press Release, 5 April 2011.