Application Note

Anritsu Advancing beyond

Dielectric Measurement Solutions for Materials Utilized in Millimeter Wave

~ Keycom × Anritsu Dielectric Constant Measurement Systems ~

1. Introduction

Trends in microwave- and millimeter-wave-based technologies

The microwave frequency band (3 to 30 GHz) is used in many familiar consumer and industrial applications. Furthermore, the use of the millimeter-wave frequency band (30 to 300 GHz) is becoming increasingly commonplace. The most active areas of microwave and millimeter-wave technology development are mobile communications systems, automotive radar, and medical applications.

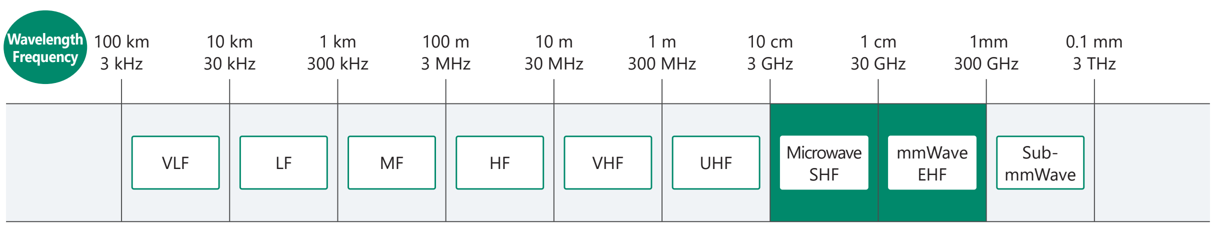

Figure 1 Wavelength/Frequency of Radio Waves.

5G mobile communications system uses the 3.7- and 4.5-GHz bands, known as "Sub6," and frequency bands below 3.6 GHz. The 28-GHz millimeter wave is also deployed in some applications. In addition, "Beyond 5G" and "6G" will utilize the millimeter-wave bands, such as the FR3 of the 7- to 24-GHz, as well as 170-GHz, and 300-GHz bands.

On the other hand, automotive radar mainly adopts radio waves in the 24- and 76-GHz frequency bands. Automotive radars are used for advanced driver assistance systems (ADAS) for collision prevention and other applications, as well as autonomous driving (AD) systems that enable safe driving without driver interaction. In addition to radar for exterior applications, there is also radar for interior sensing applications. For example, systems that prevent children from being left in cars use the 60- and 77-GHz bands.

Technology trends in dielectric measurements

High-frequency radio waves such as millimeter waves have properties including "atmospheric attenuation" and "higher straightness". In addition, in high-frequency circuits, properties such as "increased loss on printed circuit boards," "significant differences in circuit characteristics depending on the shape of the wiring pattern and the materials on the board," and "radio wave propagation characteristics depending on changes in ambient temperature". These material characteristics affect the RF Tx/Rx performance of mobile terminals and automotive radar. Therefore, to achieve better functionality and performance, materials are being developed that consider the frequency and temperature characteristics of the dielectric constant of the substrate and coating materials.

Against this background, measurement of the dielectric constant has become important for dielectric applications. For example, temperature cycling measurement is required for developing high-dielectric materials for automotive applications. There is also a growing need to be able to measure multilayer structures, such as automobile emblems, which combine body materials and surfaces, as well as composite materials composed of several materials with different properties.

Furthermore, as a material that controls the millimeter-wave radio environment, the dielectric constant of a "metamaterial," which can achieve an arbitrary dielectric constant by artificially forming a fine periodic structure smaller than the wavelength of the radio waves, is also measured. Tests that involve changes in the operating environment include not only temperature changes, but also low/high temperature, measurements while performing tensile tests under a constant load, or measurements under reduced pressure.

2. Need to Measure Dielectric Constant of Millimeter-wave Materials

Dielectric characteristics issue in 5G technology development

- Radio waves in the 5G frequency band are attenuated in the atmosphere, relative to the 4G (LTE) frequency band.
- Attenuation due to water droplets such as rainfall and condensation is particularly significant in the 28-GHz band.
- The straightness of the radio waves is notable.

5G radio waves are susceptible to attenuation due to their high frequency and thus have limited range. The same issue is also apparent with wireless LANs, such that there have been some cases where users have switched to the 2.4 GHz band due to the radio characteristics of the 5 GHz band in IEEE 802.11ax/be.

With the 28-GHz band, in particular, water droplets from rain and condensation significantly attenuate the radio waves. As a countermeasure, water-repellent paints and materials are adopted for base-station antennas to prevent water droplets from adhering. At the same time, to prevent degradation of the antenna performance, the challenge is to achieve a dielectric material that satisfies both requirements. In addition, the following topics are the subject of multiple studies:

- Building materials with high radio wave transparency, for the likes of walls and partitions
- Suppression of dielectric loss in high-frequency circuit boards
- Materials that maintain a steady without dielectric constant change for heat

To perform dielectric measurements on these materials, simulating the real-world environment is necessary while considering the change in the temperature of the measurement environment.

Dielectric characteristics issue in automotive radar development

- Anisotropy in the electrical characteristics may occur due to impurities in the substrate.
- For millimeter-wave radar, there is a need to ensure excellent radar performance without detracting from the vehicle's appearance.

The printed circuit boards for the patch antennas of millimeter-wave radar contain glass cloth or other materials, which cause anisotropy in the electrical characteristics. Anisotropy leads to discrepancies between the simulated and measured results, while the characteristics of the material may not be stable. Therefore, measures are taken to eliminate anisotropy by, for example, not using glass cloth in the substrate. In addition, automotive millimeter-wave radar is often mounted behind front/rear emblems and bumpers so as not to detract from the vehicle’s appearance. Therefore, those emblems and bumpers need to be made of metallic paint or resin that gives them a luxurious appearance while allowing millimeter waves to pass through. For this purpose, the following are being considered.

- Dielectric constant evaluation for the materials used to cover radar and materials used to install radar inside a windshield.
- Dielectric constant evaluation for radio wave absorbers installed to prevent millimeter waves reflected from vehicles and guardrails in front from being reflected off the front grille.

For such materials, a method that can measure the dielectric constant distribution is important according to the size and shape of the sample.

3. Introduction of Various Dielectric Measurement Methods

Dielectric measurement system

This section introduces the basic configuration of a system for performing dielectric measurements on the materials used in communications systems and radar. This system consists of three major parts (Figure 2).

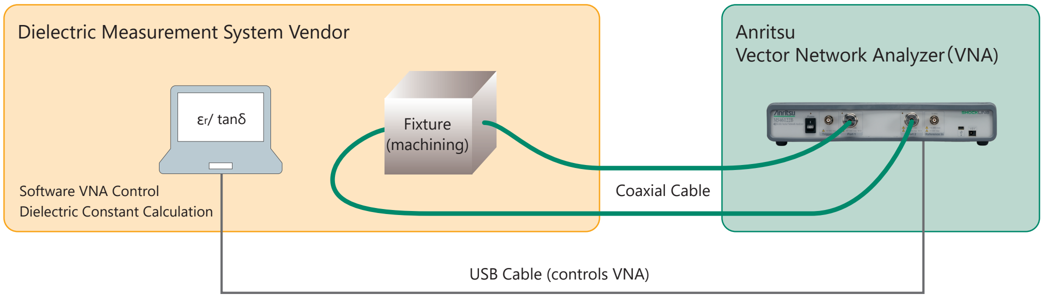

Figure 2 Basic Configuration of Dielectric Constant Measurement System.

The first is a Vector Network Analyzer (VNA), an item of test equipment that measures the amplitude and phase frequency characteristics between VNA ports. The VNA generates input signals according to the measurement conditions and captures output signals. VNAs are available as small, portable, but highly capable models with a wide range of functions. Different models are available to cover multiple frequency ranges. The most suitable VNA is selected depending on the target and purpose.

The second is a fixture for measuring the dielectric constant of a sample. A sample of the material to be measured is attached and the input/output cable from the VNA is connected. The fixture should be selected according to the type and shape of the sample and the measurement conditions.

The third is PC software that automatically measures the frequency characteristics of the sample using the VNA. The sample's dielectric constant and dissipation factor/loss tangent, which indicates the degree to which dielectric material loss changes into heat: D_F, are calculated from the measured data, and the results are displayed on the PC screen.

The fixtures and the PC software are provided by dielectric measurement system vendors, while the VNA is provided by measurement equipment vendors such as Anritsu.

Two main types of dielectric measurements

General dielectric measurements can be divided into two types (Table 1).

Table 1 Two Types of Dielectric Constant Measurement and Target Samples.

Measurement Method		Frequency Range	Target Sample							
			Resin		Powder	Ceramics	Painting Material	Adhesive	Rubber	Oil
			Plank Material	Film						
Resonator Method	A sample is placed in a resonator and the dielectric constant is determined from the change in the resonant frequency of the sample	200 MHz to 330 GHz	✓	✓	✓	✓				✓
Radio Propagation Method	A sample is placed on the path where radio waves propagate and the dielectric constant is determined from the change in the radio waves	500 MHz to 330 GHz	✓	✓			✓	✓	✓	✓

Resonator method

The first is the "resonator method. This method is suitable for measuring resins (plates and films), powders, ceramics, oils, and so forth in the frequency range of 200 MHz to 330 GHz. A sample is placed in the resonator and the resonant frequency change is measured by VNA to obtain the dielectric constant. In addition, the dielectric loss can be determined from the change in the Q value. This method is not suitable for measuring materials with a large dielectric loss, such as radar-absorbent materials.

Radio propagation method

The second method is the "radio propagation method". This method can be used to measure several samples, including resins (plates and films), paints, adhesives, rubbers, and oils, as long as they are films, 100 µm or thicker, and have a relatively high dielectric loss. A sample is placed in the path of propagating radio waves, and the dielectric constant is determined from the amount of transmission and reflection of the radio waves to the sample.

How to select a measurement method

Engineers need to select the best dielectric constant measurement method considering the following.

• Fixtures and measurement system according to the frequency range over which the sample’s dielectric constant is to be measured
• Properties of the sample (especially dielectric loss)
• Thickness and size of the sample
• Temperature and humidity at which the measurement is to be performed
• Whether the pressure is reduced.

For example, the radio wave propagation method is suitable for measuring samples with a loss tangent DF of 0.05 or greater. On the other hand, the resonator method is ideal for measuring samples with a DF of less than 0.05 and thin film samples due to the difficulty of applying the radio propagation method. Note that, even if the material is the same, the measurements to be used may differ not only between a film sample and a solid sample, but the characteristics may also differ.

Larger samples tend to be easier to detect and measure with a VNA. However, as mentioned previously, the dielectric constant itself may change with a change in shape and size. Therefore, the sample should be measured under conditions similar to the real-world environment. In addition, if necessary, engineers need to consider temperature and humidity changes that simulate the actual use environment or the use of fixtures for performing measurements under reduced pressure.

Dielectric measurements using VNA

This section introduces four methods using a VNA, the samples suitable for each, and the measurement conditions (Figure 3).

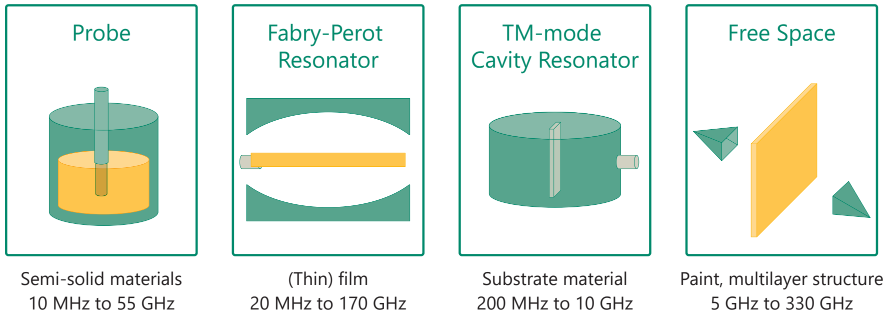

Figure 3 Dielectric Constant Measurement Using VNA.

Probe method for measuring rubber and radar-absorbent materials

The first is the "probe method" (Figure 4) based on the radio propagation method, which is suitable for measuring semi-solid materials, liquids, and solids. The dielectric constant can be measured by simply placing the probe in contact with the object. The measurement frequency range is approximately 10 MHz to 55 GHz, depending on the characteristics of the probe. The measurement range of the loss tangent is 0.001 to 10, making the method applicable to a wide range of measurement objects. The probe method is also used to evaluate the aging of rubber, concrete, and other materials. This configuration is simple and portable. This can also be brought on-site for on-the-spot measurements.

Table 2 Characteristics of Probe Method.

Sample to be Tested	Liquid, semi-solid (gel, sol), solid
Measurement Frequency	10 MHz to 55 GHz (probe dependent)
Dielectric Constant	Measurement range: 1.05 to 500 Repeatability: ±7% * dependent on VNA accuracy
Loss Tangent	Measurement range: 0.001 to 10 Repeatability: ±15% * dependent on VNA accuracy
Sample Size	Liquid: 5 ml to Rubber (solid): from 5 mm square, from 0.5 mm thick
Features	Ideal for measuring liquids, rubber, etc. Time-series measurement of long-term changes in concrete and other materials Easy to carry and perform on-site measurements

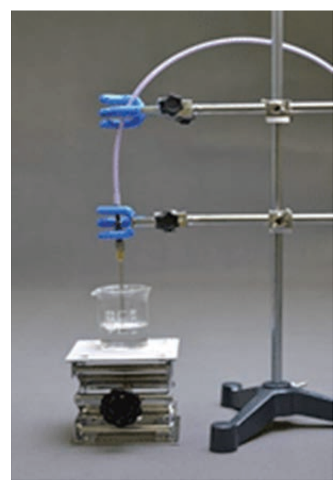

Figure 4 Probe Method.

Fabry-Perot/open resonator method for film and high-precision dielectric measurements

The "Fabry-Perot or open resonator method" is suitable for the highly accurate measuring films and sample anisotropy (Figure 5). The measurement frequency ranges from 20 MHz to 170 GHz. Highly accurate measurement is possible for materials with a small loss tangent of 0.0001 to 0.05.

In the open resonator method, a single resonator can cover the frequencies of 75.6, 79, and 81 GHz as used by millimeter-wave radar equipment and the materials used as measurement targets. In addition, Anritsu's VNA with a micro-order automatic control mechanism enables the optimization of the resonant frequency based on a sample and improves measurement accuracy.

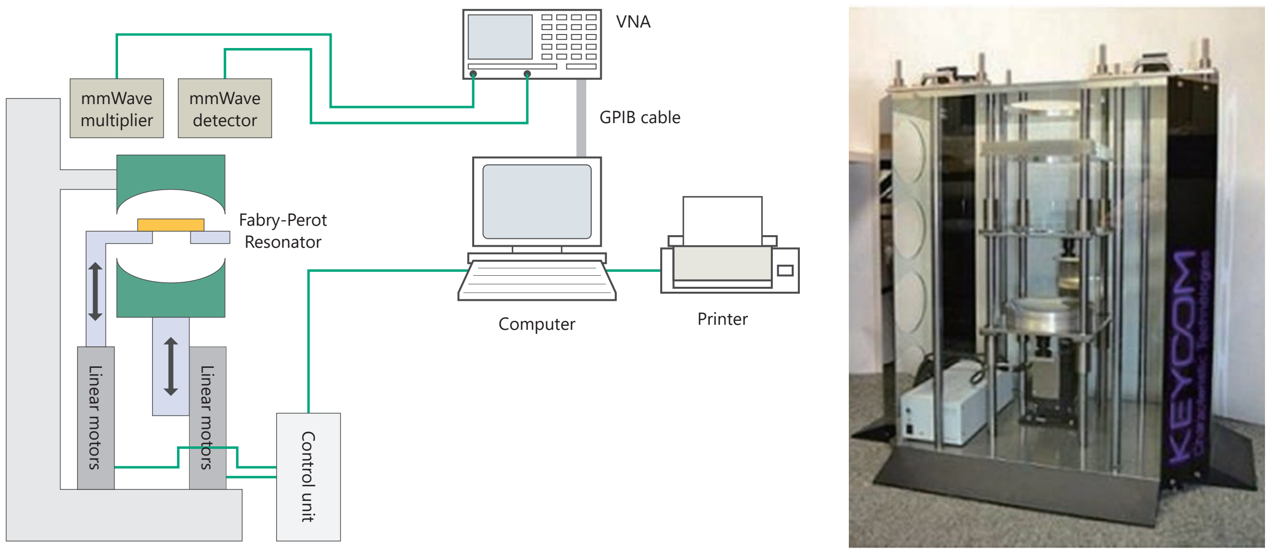

Figure 5 Measurement System of Fabry-Perot Resonator Method.

Table 3 Characteristics of Fabry-Perot Resonator Method.

Sample to be Tested	Powder, Film, Plate, Liquid, and Sample to be Depressurized (Fabry-Perot Resonator)
Measuring Frequency	20 GHz to 170 GHz
Dielectric Constant	Measuring range: 1.05 to 30 Repeatability accuracy: ±3%
Loss Tangent	Measurement range: 0.0001 to 0.05 Repeatability accuracy: ±7%.
Feature	High Q-value and accurate measurement of low-loss materials Q-value: 150,000 to 200,000 @ around 28 GHz 200,000 to 300,000@76-GHz Payments Can measure the frequency you want to measure. 75.6-, 79-, and 81-GHz measurements with a single resonator Micro-order automatic control mechanism The resonance frequency is automatically optimized according to the sample for more accurate measurements

TM cavity resonator method for measuring powders, films, plates, liquids, and samples requiring reduced pressure

The "TM cavity resonator method" is suitable for measuring powders, films, plates, and liquids, as well as for use in reduced-pressure environments (Figure 6). It is also called the "perturbation method". The measurement frequency ranges from 200 MHz to 10 GHz, covering a lower frequency range than the open resonator method. Similar to the open resonator method, this method can handle materials with a dielectric loss as low as 0.0001 to 0.05 (low dielectric loss). This method is used by many manufacturers that develop and produce powders for the printed circuit boards used in electronic devices. Multiple resonances are not used for high-precision measurements. Instead, one fixture is provided for each measurement frequency.

Table 4 Features of TM Cavity Resonance Method.

Sample to be Tested	Silica and other powders, battery materials, films, ceramics, Resins, liquids, etc.
Measuring Frequency	200 MHz to 10 GHz (single-point measurement) 300 MHz, 1, 2, 2.45, 3, 5, 5.8, 10 GHz
Dielectric Constant	Measuring range: 1 to 150 Repeatability accuracy: ±1%
Loss Tangent	Measurement range: 0.0001 to 0.05 Repeatability accuracy: ±3%
Feature	High accuracy enables accurate measurement of powders as well as resins Capable of measuring film and low-loss liquids

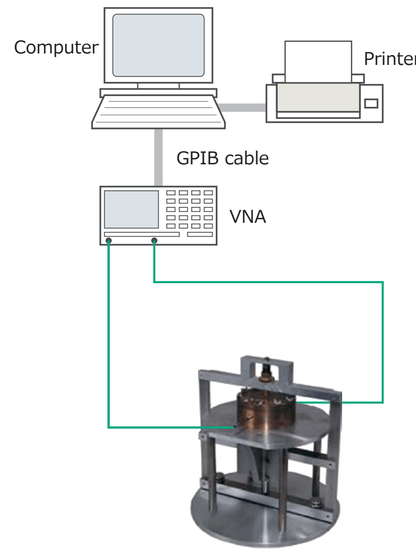

Figure 6 Measurement System for TM Cavity Resonator Method.

Free space method for measurement of paints, multilayer structures, adhesives, and liquids

The "free space method," based on the radio propagation method, is suitable for measuring paints, multilayers, adhesives, and liquids. The "free space method" includes the "frequency change method" which is suitable for measuring materials with a low dielectric loss and the "S-parameter method" for measuring materials with a high dielectric loss. The antenna of the free space method fixture is equipped with a radio wave lens to suppress unwanted radio wave reflections, allowing measurement in free space and eliminating the need for an anechoic chamber. This method is often used in the development of automotive-related equipment.

The frequency-change method measures the dielectric constant by utilizing the property whereby the frequency characteristic of the transmission attenuation when a flat sample is irradiated with radio waves is specific to the dielectric constant of the sample. The measurement frequency ranges from 5 to 330 GHz, and the same measurement method can cover a wide frequency range. This method can be applied to low-loss materials and multilayer structures, such as emblems and radomes (dome-like covers that protect radar antennas) that cover millimeter-wave radars. Furthermore, compared to the S-parameter method, this method has the advantages of its simplicity, which allows measurement simply by zero calibration, and its accuracy, which allows measurement even with fluoropolymers and synthetic diamonds. It is also easy to check the anisotropy of the sample. In addition, since the sample can be measured with a plane wave, a high measurement accuracy can be obtained with repeatability of ±1% for relative permittivity measurement and ±3% for loss tangent measurement.

With the S-parameter method, a sample is irradiated with radio waves, and the dielectric constant is determined by considering the difference between the amount transmitted through the sample and the amount reflected as being the absorption. The measurement frequency ranges from 45 MHz to 170 GHz. In addition to the dielectric constant and dissipation factor, magnetic permeability can also be measured using this method. Over a range of 18 to 170 GHz, the same fixture as the frequency change method can be used with only a software change. Note that Thru-Reflect-Line (TRL)/Line-Reflect-Line (LRL) calibration should be performed before measurement. The measurement accuracy is limited because it does not take into account reflections in those directions where there is no sensor to detect radio waves.

♦ **For frequency change method**

Table 5 Characteristics of Free Space Method (Frequency Variation Method).

Sample to be Tested	Emblem, radome, resin, glass, GFRP, honeycomb material, Wood, concrete, metamaterials, etc.
Measurement Frequency	5 GHz to 330 GHz * Fixture varies
Dielectric Constant	Measuring range: 1.5 to 150 Repeatability: ±1% or ±0.01% * Depends on the accuracy of the VNA
Loss Tangent	Measuring range: 0.0001 to 20 Repeatability: ±2% *Dependent on VNA accuracy
Sample Size	@2.6 GHz 600 mm × 600 mm @18 GHz 150 mm × 150 mm @76.5 GHz 80 mm × 80 mm
Feature	Measurement is possible in free space, eliminating the need for an anechoic chamber Suitable for samples that cannot be cut and thick materials

Figure 7 Appearance of Fixture for Free Space Method.

♦ **For the S-parameter method**

Table 6 Characteristics of Free Space Method (S-Parameter Method).

Sample to be Tested	Emblem, radome, resin, glass, GFRP, honeycomb material, Wood, concrete, metamaterials, etc.
Measurement Frequency	18 GHz to 170 GHz
Dielectric Constant	Measuring range: 2 to 200 Repeatability: Depends on VNA accuracy since the jig does not move Actual accuracy ±10%
Loss Tangent	Measuring range: 0.01 to 20 Repeatability: Since the jig does not move, VNA accuracy is reflected. Modeling Accuracy ±20%
Sample Size	@2.6 GHz 600 mm × 600 mm @18 GHz 150 mm × 150 mm @76.5 GHz 80 mm × 80 mm
Feature	Measurement is possible in free space, eliminating the need for an anechoic chamber Suitable for samples that cannot be cut and thick materials

4. Anritsu's VNA Solutions Suitable for Various Dielectric Measurements

Anritsu offers a lineup of VNAs that precisely meet a variety of measurement needs (Figure 8), including a compact and easy-to-use economy-type model with a single port configuration and a performance-type model with high output power, as the SHOCKLINE™ series. Anritsu also offers a multifunctional premium-type model as the VectorStar™ series.

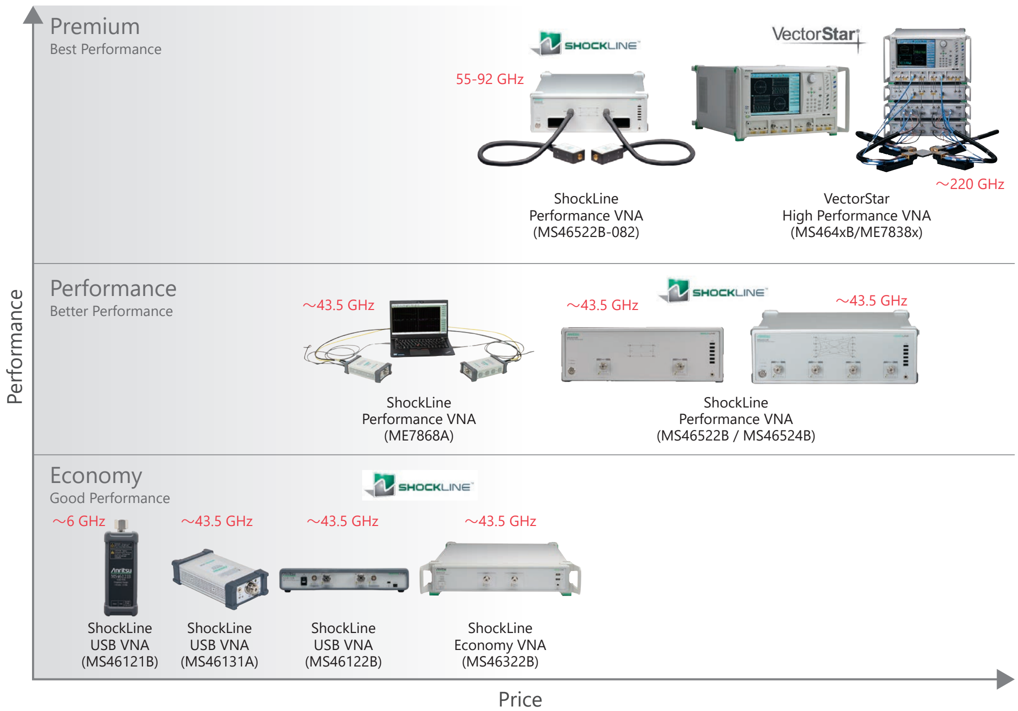

Figure 8 Anritsu's Vector Network Analyzer Lineup.

VNA for probe method

In the probe method, which has a simple system configuration, a compact and lightweight 1-port model can be brought to various locations with a simple fixture and a PC to measure the dielectric constant of equipment in actual operation or equipment that cannot be moved from the site. Anritsu offers the MS46121B, with a maximum frequency range of 6 GHz, and the MS46131A, with a frequency range of 8 GHz/20 GHz/43.5 GHz, as 1-port models to meet a variety of applications.

VNA for resonator method

Measurements using the open and TM cavity resonators require separate outputs and inputs, making a two-port VNA ideal for these applications. For the open resonator method, which covers measurements in a relatively high-frequency range, the VNAs with the following measurable frequency range are available.

MS4640B	10 MHz to 40/70 GHz to 70 GHz
ME7838A/D	70 kHz to 110/125/145 GHz

For the TM cavity resonator method, which covers relatively low-frequency bands, the following VNAs are available.

MS46122B and MS46522B	1 MHz to 8/20/43.5 GHz

VNA for the free space method

A 2-port VNA is also selected when performing the free space method. When applying one of the free space methods, the frequency change method, which can cover a wide frequency range with the same method is suitable.

MS46522B	1 MHz to 8.5/20/43.5 GHz
ME7838A/D	70 kHz to 110/110/ 125/145 GHz

Beyond 5G development has created the need to measure dielectric constants up to the 300-GHz band, and by replacing the millimeter-wave modules of the ME7838x series with frequency-extension modules, these extremely high-frequency band applications can also be handled.

For E-band automotive radar applications, the MS46522B-08x is available for frequencies between 55 and 95 GHz, and the ME7838A/D is available for the wide frequency range mentioned above.

On the other hand, for measurements in the frequency range up to 43.5 GHz, even a relatively reasonable model can be used as long as it has a 2-port VNA. An example of this is the MS46122B. If the sample to be measured has a large dielectric loss, the MS46522B, another high-output model in the SHOCKLINE series, can be selected. The MS46522B is an easy-to-use model with an ingenious design that allows the measurement cable to be easily connected to the fixture without the need for troublesome maintenance.