Characterization and Verification of Coaxial Open-circuit Primary Standards for Millimeter-wave Vector Network Analyzer Calibration

Masahiro Horibe[1], Nick Ridler[2], Martin Salter[2] and Christopher Eio[2]
[1]National Metrology Institute of Japan, Japan; [2]National Physical Laboratory, UK

Abstract

***Abstract*—This paper presents a new form of primary reference standard suitable for vector network analyzer calibration at millimeter-wave frequencies. The standard comprises a calculable, frequency-dependent, capacitor terminating a section of lossy coaxial line. The standard can be realized in any of the currently available precision coaxial line sizes used at these frequencies. The paper describes the characterization (via electromagnetic modeling and precision dimensional and electrical metrology) and validation (via precision electrical measurements) of these standards. Results are presented for a series of such standards that have been realized in the 1.85 mm line size.**

***Index terms*—primary measurement standards, millimeter-waves, vector network analyzer calibration, coaxial lines.**

I. Introduction

The increasing use of the millimeter-wave part of the electromagnetic spectrum for both commercial and scientific applications is driving the need for reliable measurements to be available at these frequencies. One way to ensure reliable measurements is to use precision coaxial connectors [1] as the reference planes for such measurements. These connectors achieve low insertion and reflection loss and are also very repeatable. As the requirement for measurements has extended into the millimeter-wave range, the design of precision coaxial connectors has also been extended to deal with these higher frequencies. For example, the 1.85 mm connector [2] (operating to at least 65 GHz) was introduced in the 1980s, and the 1 mm connector [3] (operating to at least 110 GHz) was introduced in the 1990s. Both these connectors can now be found on the front panel of precision measuring instruments, such as Vector Network Analyzers (VNAs), and devices that operate at these frequencies.

The introduction of these connector types also requires that standards are available that are fitted with these connectors so that reliable measurements can be made on these VNAs. Such standards can be found in commercially available VNA calibration kits. However, there is also a need for primary reference standards as absolute references for these measurements, to ensure that traceability to the International System of units (SI) can be achieved. To date, the availability of devices that are suitable for use as primary reference standards for these line sizes has been limited. This is because there are serious difficulties in using commercially available standards as such references to provide traceability to SI. This paper discusses these traceability difficulties and goes on to propose a new type of primary reference standard that avoids these difficulties. The paper describes the characterization of the standards using precision dimensional metrology. This is followed by the verification of the standards using precision electrical (VNA) measurements.

The standard comprises a calculable open-circuit (i.e. a frequency-dependent capacitor) terminating a section of lossy coaxial line. Such standards have previously been used successfully at lower RF and microwave frequencies [4, 5]. The challenge is now to realise such standards, with sufficient accuracy and reliability, at millimeter wavelengths in the smaller precision connectors (1.85 mm and 1 mm).

II. EXISTING COMMERCIAL STANDARDS

The traditional primary reference standard for VNA measurements at microwave frequencies is the unsupported air dielectric coaxial transmission line (or air line, for short) [6-8]. These air lines have been used to calibrate VNAs using calibration schemes such as thru-reflect-line (TRL) [9] to achieve the very highest levels of accuracy required by National Measurement Laboratories [10].

Air lines are well suited as primary reference standards because their electromagnetic properties can be calculated from first principles. These lines comprise two separate parts – a center conductor and an outer conductor. The diameters of these conductors (that define the characteristic impedance of the line) can therefore be determined easily and directly using mechanical measurement techniques (such as pneumatic gauging [11]). This shows that traceability to SI can be demonstrated easily. Air lines are therefore used regularly as primary reference standards at frequencies up to approximately 50 GHz.

However, at frequencies above 50 GHz, the line sizes become very small, i.e. 1.85 mm (for 65 GHz operation) and 1 mm (for 110 GHz operation). This reduction in size causes a number of problems:

(1) The inevitable discontinuities present at each end of the line cause significant unwanted reflections at these higher frequencies;

(2) The lines are difficult to connect due to their small size and the center conductor being unsupported;

(3) The lines are very fragile;

(4) The performance of the lines can degrade rapidly with use, due to their fragility;

(5) The lines are very expensive.

The above difficulties have led some manufacturers to introduce offset short-circuits as standards for these line sizes. Such standards can be found in VNA calibration kits for both the 1.85 mm and 1 mm lines sizes [12, 13]. These standards are used to perform three-known-loads calibrations at each VNA reference plane. However, as potential primary reference standards, these offset short-circuits have two major drawbacks:

(1) They cannot be dismantled and so it is difficult to determine the dimensions (i.e. the diameters and lengths) of the conductors. This means that it is not straightforward to demonstrate (dimensional) traceability to SI for these devices;

(2) Since the devices have fixed connectors, the center conductor will be somewhat recessed with respect to the outer conductor reference plane. Such a recession can cause significant unwanted reflections during VNA calibration, especially at millimeter-wave frequencies.

These difficulties mean that, like air lines, these offset short-circuit devices are not well suited as primary reference standards at frequencies above 50 GHz.

III. OFFSET OPEN-CIRCUITS - FABRICATION

Unsupported air dielectric coaxial line offset open-circuits (or offset open-circuits, for short) represent an alternative form of primary reference standard. They are particularly useful as standards at millimeter-wave frequencies because they do not suffer from the problems described above for air lines and offset short-circuits.

An offset open-circuit standard can be fabricated using a section of precision center conductor of the required length fitted with either a male pin or a female socket, as appropriate. A length of precision outer conductor is then connected that extends sufficiently beyond the point where the center conductor is truncated thus forming an effectively infinite length of circular waveguide below cutoff. This produces a well-defined open-circuit offset by a desired length of line (i.e. the length of line, l, that extends beyond the VNA test port reference plane) – see Figure 1. Note that there is no 'gap' in the center conductor where it joins the VNA test port