Waveguide Flange Design and Characterization of Misalignment at Submillimeter Wavelengths

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To my Parents

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Abstract

Recent technological developments are enabling components and instruments for realizing submillimeter (from 300 GHz to 3 THz) applications in a wide variety of fields, such as radio astronomy, communications, high resolution radars, imaging systems, and biomedical science. As interest in submillimeter applications have emerged, measurements of complex scattering parameters using vector network analyzers (VNAs) have become progressively extended into the terahertz frequency range. However, the measurement precision and accuracy of these instruments is limited by interconnection quality, repeatability, and the lack of traceable standards. In response to this need, the P1785 working group of the IEEE has been undertaking a study since 2008, aimed at providing recommendations for a new international standard waveguide interface for use above 110 GHz to at least 1 THz.

In this work, a new rectangular waveguide flange, the ring-centered flange, has been presented. The superior alignment, full backward compatibility, and simple design make it one of the most robust candidates being considered by IEEE P1785 group as a new international standard for waveguide interfaces for use above 110 GHz. In order to evaluate precision and accuracy of flanges at submillimeter-wave frequencies, several different techniques have been discussed and compared. Connection repeatability has been measured using VNA time-gating method and the load-separation method. The true reflection coefficient for a pair of flanges is characterized with a calibration technique insensitive to flange misalignment. Experimental results for various flange designs are examined and discussed in detail.

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Chapter 1

Introduction

1.1 Overview of Submillimeter-Wave Application

The submillimeter-wave band comprises frequencies has from 300 GHz to 3 THz. This region of the spectrum found applications in fields such as radio astronomy and atmospheric remote sensing [1] [2], yet remains a relatively unexplored segment of electromagnetic spectrum. Recent technological developments are enabling components and instruments for realizing submillimeter applications such as short range, high bandwidth communications [3], high resolution radars [4] [5], imaging systems [6], and biomedical science [7] [8]. Evidence of the new interest in submillimeter systems includes the establishment of a new journal, the IEEE Transactions on Terahertz Science and Technology. Although interest in submillimeter applications continuous to grow, the test and measurement infrastructure for this frequency range is just now being realized and remains relatively underdeveloped [9].

Among the most important instruments for characterizing RF and millimeter-wave devices is the vector network analyzer. The technology of vector network analyzers has been dramatically

improved since it was first commercially introduced by Hewlett Packard in 1967. In recent years, VNA measurements of s-parameters have been progressively extended into the terahertz frequency range and state-of-the-art instruments operating up to 1 THz are now commercially available [10] [11]. Figure 1.1 shows a photograph of a VNA with 750 – 1100 GHz (WR-1.0 or WM-250) external extension modules [12]. In addition, terahertz on-wafer probes operating at frequencies up to 750 GHz have been recently developed [13] [14], further broadening the measurement capabilities for submillimeter micro-fabricated devices.

Figure 1.1 Vector Network Analyzer from Agilent (model: N5245A PNA-X) with 750 – 1100 GHz frequency extension heads from Virginia Diodes, Inc. (VDI) [12].

1.2 Flange Misalignment

Rectangular waveguide is the most common transmission medium used for measurement instruments at millimeter and submillimeter wavelengths. Rectangular waveguide represents a reasonable trade-off between low loss and high power handling, as well as permitting techniques for integration of devices with antennas and other components. Numerous waveguide components exist, including circulators, isolators, attenuators, loads, mixers, and amplifiers. Shown in Figure 1.2 are a few examples of rectangular waveguide components.

(a)

(b)

(c)

(d)

Figure 1.2 Examples of rectangular waveguide components. (a). waveguide taper; (b). heterodyne mixer; (c). waveguide tripler; and (d). waveguide bends. Pictures are from www.microwaves101.com, and www.vadiodes.com.

Interconnection between waveguide components is generally accomplished with flanges. A typical waveguide flange is aligned by pins and mating pin holes. However, due to the practical machining tolerances on pins and holes, a flange misalignment is always possible during waveguide connections, as illustrated in Figure 1.3. This misalignment degrades measurements significantly at high frequencies, where waveguide dimensions are small and misalignment represents a significant fraction of the waveguide aperture. Figure 1.4 shows a WM-380 rectangular waveguide test port seen through a shim under a microscope. The shim has been intentionally pushed in each direction to produce the maximum possible misalignment in the waveguide H- and E-plane. As the flange misalignment becomes comparable with waveguide dimensions, its effects are not negligible for precision measurements in the submillimeter-wave frequency range.

Figure 1.3 Illustration of waveguide flanges and their misalignment due to limited machining tolerances [23].

Figure 1.4 Example photos for a waveguide test port seen through a milled waveguide shim in the 500–750 GHz (WR-1.5 or WM-380) frequency band. The shim has been artificially pushed to the end in each direction to produce a maximum possible waveguide misalignment in (a) H-plane, and (b) E-plane.

Electromagnetically, the junction of a pair of mated waveguides, where one of the waveguides has an error in its aperture dimensions or a misalignment error relative to the other guide, is known to be equivalent to a frequency dependent shunt susceptance at the plane of the waveguide junction [15,16]. Figure 1.5 illustrates waveguide offsets in E- and H-plane, respectively, with their equivalent circuit models. For a misalignment in the H-plane the susceptance is negative (inductive), and for a misalignment in the E-plane the susceptance is positive (capacitive). Harrington derives expressions for these susceptances assuming a TE₁₀ mode field distribution at the junction aperture, and these are given equation (1.1) and equation (1.2), respectively [16].

$$B_C = \frac{4a}{\lambda_g Z_0} \sum_{n=1}^{\infty} \frac{\sin^2(n\pi c/b)}{(n\pi c/b)^2 \sqrt{n^2 - (2b/\lambda_g)^2}} \quad (1.1)$$

$$B_L = -\frac{4\lambda}{\eta\pi^2b} \left(\frac{c}{a}\right)^2 \sum_{m=2}^{\infty} \left[\frac{\sin(m\pi c/a)}{1 - (mc/a)^2} \right]^2 \sqrt{\left(\frac{m}{2}\right)^2 - \left(\frac{a}{\lambda}\right)^2} \quad (1.2)$$

Figure 1.5 Symmetrical (a) E-plane, and (b) H-plane displacements at a waveguide junction and their equivalent circuits [16].

It has long been known that the effect of flange misalignment becomes more and more significant and imposes a serious limitation on repeatable S-parameter measurements at frequencies greater than ~ 100 GHz [17] [18] [19] [20]. In practice, waveguide flange misalignment can be as large as $100 \mu\text{m}$ with standard machining tolerances and $65 \mu\text{m}$ with precision fabrication methods [21]. In Figure 1.6 and Figure 1.7, the reflection coefficient for a pair of rectangular waveguides with misalignment in H-plane, E-plane, as well as rotational is

shown [22]. These simulations show that the E-plane misalignment is dominant, producing a large reflection for a given offset at high frequencies. The rotational misalignment effect is relatively insignificant by comparison. For even a 25 μm misalignment in the waveguide E-plane, the reflection is potentially as high as -20 dB at 750 GHz, and -15 dB at 1100 GHz. This is clearly unacceptable for high precision measurements. Furthermore, flange misalignment introduces biased error in measurements of calibration standards, thus pose a limitation on VNA calibration precision [23] [19].

(a) H-plane misalignment

(b) E-plane misalignment

Figure 1.6 Reflection coefficient for a pair of rectangular waveguides with misalignment in (a) H-plane, and (b) E-plane [22].

Figure 1.7 Reflection coefficient for a pair of rectangular waveguides with rotational misalignment [22].

1.3 Flange Standards

The most widely used waveguide interface standard at millimeter and submillimeter frequencies, the MIL-DTL-3922/67C (UG-387 or 750-round), and its enhanced versions, have long been known to be inadequate above ~ 100 GHz. Although much effort has been expended in improving waveguide interfaces over the years, hardware from different laboratories and

companies is often incompatible [17] [24]. For these reasons, it is clear that there is a need to standardize flanges to meet new and emerging applications.

Since 2008, the P1785 working group of the IEEE has undertaken a study which is expected to lead to recommendations for a new international standard waveguides interface for use above 110 GHz [25] [26]. The requirements for a standard waveguide flange include: repeatable operation to at least 1 THz with low reflection; backward compatibility with existing interfaces and waveguides below 325 GHz; ease of machining; non-sexed to avoid the need for male and female flanges; and anti-cocking. In recent years, several innovative designs have been identified as candidates for their excellent potential with regard to repeatability over the standard UG-387 types [27] [28] [29]. A considerable amount of work has been done by the working group for theoretically analyzing and comparing all candidate flanges. At present, precise measurements of flange performance are needed and are of great interests for evaluating candidate interfaces.

Experimentally characterizing flange performance at submillimeter-wave lengths is challenging, as the reflection coefficient for a pair of well-aligned flanges is very small. To measure it, a calibration method is needed which is not affected by flange misalignments of the same order as those being characterized. Most calibration techniques in use today are limited in precision by flange error and are not suitable for characterizing flange performance. Secondly, calibration also requires either a matched termination of return loss greater than that of the interface being measured or an alternative standard with an accurately known complex reflection coefficient. For these reasons, little work has been done on precisely characterizing flange mismatch at submillimeter frequencies.

1.4 Organization of This Dissertation

In this work, waveguide flange repeatability and accuracy at submillimeter frequencies is experimentally characterized by using different techniques. Chapter 2 presents a discussion of waveguide flange designs and features, including a new ring-centered flange that has been developed at the National Radio Astronomy Observatory (NRAO), Virginia Diodes, Inc. (VDI) and University of Virginia (UVA). The design is simple, is backward compatible with UG-387 flanges, and provides superior alignment compared to existing flange types. It is among one of several candidate flanges which are currently being considered by IEEE P1785 group as a new international standard waveguides interface for use above 110 GHz. Chapter 3 presents measurements on flange connection repeatability using two different techniques. Results for various types of flange are presented and compared. In Chapter 4, the flange absolute mismatch is characterized using a calibration insensitive to flange misalignment. Results are presented for different flanges and compared with theory. As members of IEEE P1785 working group, this work is useful to allow comprehensive evaluation of all candidate flanges.

Chapter 2

Waveguide Flange Standards

2.1 Introduction

Rectangular waveguide is the most common transmission medium used for measurement instruments at millimeter and submillimeter wavelengths. The round MIL Spec MIL-F-3922/67B flange was released in the 1975 as an international standard interface to be used up to 110 GHz. A smaller mini-flange (MIL-3922/74 or TRG-714) was later specified for use through 325 GHz, but no universal industry standard has been defined beyond 325 GHz. Figure 2.1 lists the main US MIL Spec flange standards for use at 18 GHz and above [24]. In most bands, there are two types of standards specified. The current version of the MIL Spec standard is 0.75" diameter round UG-387. It has been widely applied in systems through 110 GHz and is known for being sufficiently precise for low return-loss measurements. Above 110 GHz, experience from researchers and engineers has found that this complex mini-flange standard has relatively poor flange-to-flange contact, less predictable performance, and is more difficult and expensive to machine than the UG-387 type. For these reasons, the community became largely dissatisfied

with this mini-flange design and preferred using modified variations of UG-387 flanges with tighter tolerances on the holes and alignment pins to meet their own needs above 110 GHz [30]. Although a considerable amount of work has been done to improve waveguide interfaces over the years, hardware from different laboratories and companies is often incompatible.

TABLE I: MIL Spec Flanges for Small Waveguides

WR-#	Frequency GHz	MIL-F- 3922/74-( ) 0.373" dia. (TRG-714 type)	MIL-F- 3922/67B-( ) 0.75" dia. (UG-387 type)	MIL-F- 3922/67B-( ) 1.125" dia. (UG-383 type)	MIL-F- 3922/54-( ) 0.75" sq. (UG-599)	MIL-F- 3922/54-( ) 0.875" sq.
3	220-325	005	003M			
4	170-260	004	004M			
5	140-220	003	005M			
6	110-170	002	006M			
8	90-140	001	008M			
10	75-110		010			
12	60-90		009			
15	50-75		008			
19	40-60			007		
22	33-50			006		
28	26.5-40			005	003	
42	18-26.5			004		001

Figure 2.1 Previous MIL Spec waveguide standards for use at 18 GHz and above [24]. Universal industry standard ends at 325 GHz.

As interest in submillimeter applications have emerged, measurements of complex scattering parameters using vector network analyzers (VNAs) have become progressively extended into the terahertz frequency range [10]. However, the measurement precision and accuracy of these

instruments is limited by interconnection quality, repeatability, and the lack of traceable standards [31] [32].

For these reasons, the importance of establishing a new standard which allow the development of compatible components for the emerging submillimeter applications cannot be understated. In response to this need, the P1785 working group of the IEEE has been undertaking a study since 2008 [33], aimed at providing recommendations for a new international standard waveguide interface for use above 110 GHz to at least 1 THz.

This chapter focuses on discussion of the development and features of various waveguide flanges that are currently being used or being considered as potential standards by the IEEE P1785 study group.

2.2 Standard UG-387 Flange

In the 1960s and early 1970s, a similar flange standardization issue arose in the community as is happening today [34]. Different companies and organizations developed their own interfaces, thus resulting in a loss of cross-compatibility. After competing over other designs, the round MIL Spec MIL-F-3922/67B flange was released in the 1975 as an international standard interface for use up to 110 GHz. The most significant feature for this flange is the use of alignment pins and holes. Figure 2.2 shows the design for the current version of the MIL Spec, 0.75" diameter round UG-387. It has a four-pin indexing pattern for alignment with two press-fit pins and two clearance holes on each flange, at a 45 ° angle to the waveguide aperture; a raised boss in the center around the waveguide aperture; and a four-bolt circle pattern located outside

the raised boss area. This standard flange has been widely applied in millimeter-wave systems, and is known to be sufficiently precise for low return-loss measurements through 110 GHz [24].

There are also problems posed by the standard UG-387 flange. Firstly, the alignment accuracy of the design is limited by the clearance between the pins and pin holes, position of the pins and pin holes, as well as the perpendicularity of the pins relative to the interface faces. The maximum clearance between the alignment pins and their mating pin-holes is 0.0035" radially, and the tolerances on pin and pin-hole position are 0.001" and 0.0015" radially, allowing a possible misalignment between waveguides of 0.006". From simulation results in Figure 1.6, this could result in a return loss as low as 24 dB at 110 GHz, 12 dB at 220 GHz, but only 8 dB at 330 GHz. Secondly, cocking of mated flanges can occur due to the bolt circle outside the raised boss area. It is very difficult to get a perfectly flat connection. Thus tightening the four screws must be done very carefully to avoid cocking one flange relative to the other, leaving a gap, and possibly permanently deforming the mating surfaces. Connection repeatability as a result is found to be poor due to the sloppy fit of the indexing pins and cocking of the mated flanges.

(a)

(b)

Figure 2.2 (a) Mechanic drawing from the Custom Microwave catalog, and (b) picture for the standard UG-387 flange. The pins are of diameter 0.0615" -0.0005/+0.0000, and holes are 0.0670" -0.000/+0.001 in diameter. Maximum Waveguide Offset is about 0.006".

2.3 Modified UG-387 Flanges

A mini-flange (MIL-3922/74 or TRG-714) was specified for higher frequency use through 325 GHz, but no universal industry standard has been established beyond that. Drawings and pictures for the mini-flange are shown in Figure 2.3. It has a smaller diameter 0.373" (9.474 mm) than the UG-387 style, and has no screw or pin holes in the E-plane, a desired characteristic for split-block waveguide components. The Mil Spec tolerances on the mini-flange allow a maximum lateral misalignment of 0.081 mm (0.0032") between waveguides. However, there are several technical issues limiting use of this flange. It is expensive to machine; and it is not possible to view the interface contact. Experience has found that this mini-flange has inferior flange-to-flange alignment and less predictable performance than the standard UG-387 types above 90 GHz [24]. The reason is that the mini-flange has a relatively complex design, which requires a high degree of parallelism between front and rear faces of each flange as well as tight dimensional tolerances on the coupling hardware itself. For these reasons, this mini-flange is not widely adopted by the industry and several modified variations of UG-387 flanges with tighter tolerances on the holes and alignment pins are preferred.

(a)

(b)

Figure 2.3 MIL Spec mini-contact flange (MIL-3922/74 or TRG-714). (a) Mechanical drawing from the Custom Microwave catalog. Dimensions are in inches. (b) Picture of the flange.

There are several different anti-cocking variations of UG-387 flanges used in different companies, such as Anritsu, Flann Microwave, and Hewlett Packard. They are all compatible with the standard UG-387 design, but add an anti-cocking characteristic on each flange and have tighter tolerance on alignment pins and holes. Sometimes they include a pair of holes on the boss area, to be used optionally with one or two removable inner pins for more precise alignment. Figure 2.4 shows an example modified UG-387 flange from Hewlett-Packard. Compared with standard UG-387 flange, this design has much tighter tolerances on the outer pins and mating pin holes, giving a maximum misalignment 0.076 mm (0.003"). But this value varies with different manufacturers.

Figure 2.4 An example modified UG-387 flange from Hewlett-Packard. It has anti-cocking characteristics, a pair of inner alignment holes, and is fully compatible with the standard UG-387 type of flange. Dimensions are in mm (from Hewlett-Packard).

Tightening the tolerances on alignment pins and pin holes is not a final solution for precise flange alignment at higher frequencies. Due to the machining limitations, the practical limit of waveguide alignment using non-interfering pins appear to be about 0.071 mm (0.0028”), which corresponding to a return loss of about 37 dB at 110 GHz, but only 19 dB at 330 GHz, and 2 dB at 1100 GHz. This degree of misalignment is clearly not acceptable for many applications at submillimeter wavelengths (such as vector network analyzer calibration).

Over the years, much effort has been devoted to developing variants of the UG-387 standards to meet specific needs in different companies, such as Aerowave, Agilent (HP), Custom Microwave, Flann, Maury Microwave, Millitech, and Oleson Microwave Laboratories, as well as several research laboratories and universities. This has resulted in loss of cross-compatibility and further complicates the possibility of millimeter waveguide connection standards [24] [20] [35]. Adapters between incompatible waveguides introduce degradation in the precision of measurement systems. For these reasons, it is necessary to establish new standards to maximize inter-compatibility and minimize the costs associated with the proliferation of incompatible hardware [36] [17].

A standard waveguide flange should provide a high degree of repeatability and alignment precision for operation to at least 1 THz, without requiring undue skill and attention of the user. It should be backward compatible with existing interfaces and waveguides below 325 GHz for cost benefits purpose, should be robust against damage to precision surfaces, should prevent cocking, should be sexless, and should be relatively simple to machine and manufacture.

Recent years, several proposals for more precise flange designs have been published and identified as candidates for significant improvement in accuracy and precision over the common

UG-387 and its higher-frequency variants. Details of these flanges are described in the following sections.

2.4 Lau-Denning Flange

In 2007, Lau and Denning at Oleson Microwave Laboratories (OML) developed a new waveguide flange design that addresses machining tolerance limitations [28]. Their flange is illustrated in Figure 2.5, and the principle features of the design include a male flange with a boss and a mating female flange with a close fitting socket. Alignment relies on the concentricity of the waveguide apertures with the boss and socket. This design reduces the number of critical features subject to exacting tolerances; as a result, improved alignment accuracy and repeatability are achieved. However, the design has three significant limitations: it is not backward compatible with the existing UG-387 interface; it is not sexless; and the contact surface on the female flange is recessed and therefore not accessible for cleaning and lapping to repair damage.

Figure 2.5 The original Lau-Denning OML flange proposed in 2007. It includes a male flange with a raised boss and a mating female flange with a close fitting recessed socket [28].

In 2012, the Lau-Denning OML design was modified to improve its compatibility with the UG-387 type [37]. Shown in Figure 2.6 are photographs for the modified Lau-Denning flange. The primary change is the diameter of the male boss (and the diameter of the mating socket on female flange) has been increased to be the same as the UG-387 style. In addition, each flange includes a pair of inner alignment holes as do several modified UG-387 variants. Thus both the male and female interfaces become compatible with existing UG-387 types. A customized adapter shim is required for traditional through-reflect-line (TRL) [38] and line-reflect-line (LRL) [39] VNA calibrations and is shown in Figure 2.7.

Figure 2.6 The modified Lau-Denning OML design proposed in 2012. Left: male interface with a raised boss. Right: female interface with a recessed socket [28].

Figure 2.7 Adaptor shim for the modified Lau-Denning flange. Left: photo for the customized quarter-wave shim; Right: photo showing the shim sitting in place on the female flange [28].

2.5 Ring-Centered Flange

The ring-centered flange concept was first described by Kerr and Srikanth in 2009 [27], and the interface was further developed in a collaboration between NRAO, VDI, and the University of Virginia. As shown in Figure 2.8, the flange has a precisely machined boss centered on each waveguide aperture and a coupling ring which aligns a mated pair of bosses. The alignment accuracy is determined by both the clearance between the coupling ring and the boss, and the alignment of the boss with the waveguide aperture. Like the UG-387 standard, it is sexless, and contact surfaces are not recessed, facilitating cleaning and lapping to repair damage. It also includes an anti-cocking rim to prevent cocking during connections. The maximum misalignment is expected to be within 0.0025 mm (0.0001”), which results in loss about 26 dB at 600 GHz, and 16 dB at 1100 GHz according simulation results shown in Figure 1.6.

Figure 2.8 The ring-centered waveguide flange concept [27].

2.5.1 Design and Features

Figure 2.9 shows photographs of waveguide test pieces with the ring-centered flange, which are designed using the E-plane split-block technique and fabricated on a CNC milling machine.

The advantages of the ring-centered flange include [40]:

- 1) Improved alignment precision compared to the older UG-387 type. The alignment between the waveguide apertures depends on the clearance between the coupling ring and bosses and the alignment of the bosses with their waveguide apertures. Alignment pins are used only to provide angular alignment. To prevent the pins interfering with the centering function of the ring and bosses, oversize pin holes are used. The pin clearance holes are chosen of 1.702 mm (0.067") diameter for compatibility with the standard UG-387 interface, and pins are of 1.562 mm (0.0615") diameter as for the original MIL specification. This combination provides sufficient pin clearance not to interfere with the alignment of the bosses by the ring.
- 2) The flange is sexless; all flanges are identical. This simplifies manufacture of the flange and allows components to be used more flexibly.
- 3) Backward compatibility with existing UG-387 flanges without adaptors. When a ring-centered flange is mated with a UG-387 flange, no ring is used, and alignment is provided by the pins and the mating pin holes. Flange alignment and repeatability in this case will be the same as for the standard UG-387 types.
- 4) The mating surface of the ring-centered flange is not recessed, which facilitates cleaning and lapping to repair damage. It also has an anti-cocking rim which has been incorporated into many of the newer implementations of the UG-387 interface.

Figure 2.9 Photographs of WR-5 (140 – 220 GHz) test pieces with ring-centered flanges. Left: the interface showing the boss and anti-cocking rim. Right: the interface with the coupling ring in place. Note the square holes above waveguide apertures are not functional, they exist because we removed the split blocks alignment pins after assembly [40].

Shown in Figure 2.10, the coupling ring is made from commercially available precision stainless steel shim bushing stock which is available with outside diameter 9.525 mm (0.3750”) and inside diameter 7.938 mm $+0.005/-0.000$ mm (0.3125” $+0.0002/-0.0000$) [41].

During development of the ring-centered flange, it was realized that the original design is not practical for traditional two-port TRL and LRL VNA calibrations using waveguide shims due to the presence of the ring between a pair of flanges. This issue is addressed in the following section.

Figure 2.10 The ring-centered waveguide flange coupling ring (right) and the commercial precision stainless steel bushing stock (left) [40].

2.5.2 Improved Ring-Centered Flange

Several modifications on the ring-centered flange design were proposed in 2010 to facilitate TRL and LRL VNA calibrations using customized “through” waveguide shims. Drawings of the modified ring-centered waveguide flange and coupling ring are presented in Figure 2.11. The proposed modifications of the ring-centered waveguide flange include [42]:

- 1) A larger coupling ring with inside diameter 0.3750” (tolerance $+0.0002/-0.0000$) and outside diameter 0.4375” (tolerance $+0.0000/-0.0002$). The ring is made from precision stainless steel shim bushing stock which is commercially available with the above tolerances [41].
- 2) Two additional dowel holes with diameter 0.0625” $+0.0005/-0.0000$ located adjacent to the waveguide broad walls in each boss.

With the above modifications, the ring-centered waveguide flange is fully backward compatible with all known variants of the UG-387 interface, including those of Agilent, Flann,

Maury, and Rohde & Schwarz, which include the additional inner dowel holes. Furthermore, TRL and LRL calibrations of VNAs with ring-centered waveguide flanges are now practical as one or both the inner dowels can be used to provide angular alignment of the "through" calibration shim. Sufficiently precise angular alignment is achieved using relatively loose dowels, which allows the ring to center the shim on the waveguide apertures without mechanical interference. However, the ring-centered design is not expected to have quite the same ultimate precision as the Lau-Denning interface discussed in earlier section because there is an additional interlocking component (the ring) with its associated tolerance.

Photographs of test pieces with the improved ring-centered flanges designed for use in the 330 – 500 GHz (WR – 2.2 or WM – 570) frequency band are shown in Figure 2.12. A customized waveguide shim with ring-centered flange to assist TRL calibration can be fabricated using KMPR based microfabrication process [43] [44], and is shown in Figure 2.13. It should be noted that the improved ring-centered flange is also fully compatible with the original ring-centered design if an adapter ring is used. This can be made from the same precision bushing stock used for the smaller rings, which fits inside the larger ring precisely.

(a)

(b)

Figure 2.11 Drawings of (a) the improved ring-centered waveguide flange and (b) the coupling ring. Dimensions not shown are to the UG-387 standard [42].

Figure 2.12 Photographs test pieces with improved ring-centered waveguide flanges designed in the 330 – 500 GHz (WR-2.2 or WM-570) frequency band. Left: the interface showing the larger 0.375" boss and inner pair dowel holes. Right: the interface with the 9.525 mm (0.375") coupling ring in place [42].

Figure 2.13 The micro-fabricated quarter-wave shim with modified ring-centered flange in the WM-570 frequency band. SEM image of the waveguide is shown on the right [43].

2.6 Oshima Flange

Since commencing the work on the ring-centered flange, we have become aware of a similar scheme developed in Japan for use on submillimeter wavelength receivers [45]. Instead of an alignment ring, a plate is used between the flanges with a hole which aligns bosses on the flanges. However this design is not compatible with the UG-387 standards

Horibe et al. recently modified the Oshima flange to be compatible with the standard UG-387 types [46] [47]. The modified “Oshima” flange has a precise machined outer diameter of flanges and alignment is established by a precision coupling ring. Figure 2.14 shows photos for modified Oshima flange and a customized waveguide shim for use as a “line” in two-port TRL or LRL calibrations. The diameter of the outside of the flange is 19.050 mm (tolerance +0.000 mm/-0.005 mm), and the diameter of the alignment ring is 19.050 mm (tolerance +0.005 mm/-0.000 mm). The flange also includes a pair of inner holes for compatibility with some modified UG-387 variants. There is an additional precision dowel slit with width 1.500 mm (tolerance +0.020 mm/-0.000 mm) located adjacent to the threaded hole.

Figure 2.14 Modified Oshima flange (bottom left), alignment ring (top), and customized waveguide shim(bottom right) [29].

2.7 IEEE P1785 Working Group

To meet the emerging interests of the submillimeter community and improve compatibility between different manufacturers, the P1785 working group of the IEEE was established in 2008 to undertake a study, which is expected to lead to recommendations for standard waveguides and interfaces for use above 110 GHz [48] [26] [49]. The IEEE P1785 standard, when published, will be a new international standard.

As of this writing (2012), several different flange designs are being considered by the P1785 working group of the IEEE for evaluation as possible standards for waveguide interfaces. These are all based on the UG-387 type but have additional dowels or an alignment ring to provide more precise alignment and repeatability. As shown in Figure 2.15, the primary candidates under consideration are:

- 1) Precision UG-387 interface A1. The flange has a pair of inner holes of equal size located in the E-plane. When connecting two waveguides together, precision pins are inserted into these inner alignment holes to achieve improved alignment (when compared with the traditional UG-387 interface). Two inner alignment dowels are of different sizes: a larger close-fitting dowel D1 provides a very good lateral alignment and a smaller loose-fitting dowel D2 constrains any significant rotation, about the first pin, of one flange with respect to the other.
- 2) Lau-Denning interface as described in section 2.4, in which alignment is achieved by the precision raised boss and recessed socket.
- 3) The ring-centered flange as described in section 2.5. Alignment of the ring-centered flange depends on the coupling ring which is a close fit on the central bosses. A relatively loose outer pin provides angular alignment.

Figure 2.16 compares the advantage and disadvantages of each flange. The table was developed by A. R. Kerr et al. Theoretical analysis on the flange misalignment for each candidate design has also been performed by the P1785 group. Figure 2.17 shows an example analysis of theoretical performance of flanges in the WM-250 frequency band (presented by A. R. Kerr at the June 2012 P1785 Meeting). However, work is still ongoing for measurements of flange performance and comparison with their predicted values. The next two chapters of this thesis will focus on experimentally characterizing repeatability and accuracy of flange misalignment.

(a) Precision UG-387 interface A1

(b) Ring-centered flange

(c) Lau-Denning boss & socket flange

Figure 2.15 Flanges are currently under consideration by IEEE P1785 group (as 2012), (a) Precision UG-387 interface A1 using two unequal inner dowels; (b) ring-centered flange; and (c) Lau-Denning boss & socket flange.

	Interface PROs & CONs		
	1 -- Candidate-A1	2 -- Ring-Centered	3 -- Lau-Denning II
Compatibility with UG-387 and variants	Compatible with UG-387 and Hesler et al.	Compatible with 1, UG-387, & Hesler et al.	Not fully compatible with any others.
Sexless	Yes	Yes	No
Ease of use	Requires two dowels of slightly different sizes -- the wrong choice will cause damage, or poor alignment.	Uses a single standard ring	Simple-- no additional coupling hardware required.
Ease of cleaning and maintenance	Good	Good	Harder to clean; can not lap mating surfaces
Split-block components (E- or H-plane)	Maintaining dowel hole tolerance requires very precise alignment between block halves during assembly of components split in the E-plane	Using rings during assembly provides 3-axis alignment.	Same as 1
Wear and tear	Dowel holes enlarge by a few microns after a lot of use	Have not seen significant wear on bosses (much larger contact area than dowels)	Should be good
Manufacturing requirements	Can be made on a lathe, but needs jig-borer or CNC mill for	Same as 1	Requires CNC mill.
Through shims for TRL cal	With thick shim, use long dowels.	Need two-piece shims. With thick shim, use thick ring.	Shim thickness limited by boss height

Figure 2.16 Discussion on Pros and Cons for each candidate flange. This table is made by Kerr, et al. group members of the IEEE P1785.

Example of Alignment Analysis Spreadsheet

Ring-centered interface -- using UG-387 outer pins

Metric		Nominal (mm)	Tolerance (mm)		Min (mm)	Max (mm)	Position tolerance zone diameter (mm)	
			+	-				
1	Boss diameter	Db	9.525	0.000	0.005	9.520	9.525	Z1 = 0.005
2	Ring diameter	Dr	9.528	0.003	0.000	9.528	9.530	--
3	Outer pin hole diameter	Dh	1.702	0.025	0.000	1.702	1.727	Z2 = 0.051
4	Pin diameter	Dp	1.562	0.000	0.013	1.549	1.562	Z3 = 0.076
5	Pin hole PC diam	PCD	14.288	--	--	--	--	--

Interference test -- Want $(D_{r,min} - D_{b,max}) + (D_{h,min} - D_{p,max}) - (Z1 + Z2/2 + Z3/2) \geq 0$

$$(D_{r,min} - D_{b,max}) + (D_{h,min} - D_{p,max}) - (Z1 + Z2/2 + Z3/2) = 0.0740$$

				% of <i>a</i> for WM250		Approx S11 for WM250 (dB)
8	Max misalignment in the a direction*	0.015	mm	6.0	%	-28
9	Max misalignment in the b direction*	0.015	mm	6.0	%	-24
10	Maximum angular misalignment	2.1	deg	--		-55

* Approximate dB values from Figs. 4-7 of NRAO EDTN215: [Link](#)

	<i>a</i> -misalignment microns	<i>b</i> -misalignment microns	S11 max in WM-250 dB*
Candidate A1 (unequal dowels)	19	14	-25
Ring-centered (+ UG-387 outer pins)	15	15	-24
Hesler et al. (improved UG-387)	60	60	~ -3
UG-387	152	152	large

* Approximate dB values from Figs. 4-7 of NRAO EDTN-215

In all cases, min dowel-to-hole clearance is 3 microns (in diameter)

Figure 2.17 Example theoretical analysis of interface misalignment. Presented by A.R. Kerr at the June 2012 P1785 Meeting.

Chapter 3

Waveguide Flange Connection Repeatability

3.1 Introduction

Connection repeatability is characterized by the vector difference between a set of measurements corresponding to separate connections. Better repeatability results in a smaller vector difference and will appear in the display as a more negative log magnitude. Connection repeatability is critical in precision measurements, especially in submillimeter-wave applications, and measurements of flange performance are usually performed by using the reflection measurements with a vector network analyzer [50] [51].

In this chapter, waveguide flange connection repeatability is characterized using two different techniques, time-gating and the load-separation method. Each technique will be described and measurements for different designs over various frequency bands will be presented and discussed.

3.1 Time-Gating Technique

One method for measuring flange connection repeatability is by employing a VNA's time domain analysis and time gating functions. Vector network analyzers measure the response of a device under test (DUT) in the frequency domain and then mathematically calculate the inverse Fourier transform of the data to yield the time domain response. Specifically, an inverse discrete Fourier transform (IDFT) is performed. Given a set of N samples, $x[n]$, $n = 0, \dots, N-1$, the DFT is defined as [52]:

$$X(n) \equiv \sum_{k=0}^{N-1} x[k] e^{j(2\pi kn / N)}, n = 0 \dots N-1$$

The inverse DFT (IDFT) is:

$$x(k) \equiv \frac{1}{N} \sum_{n=0}^{N-1} X_n e^{-j(2\pi kn / N)}$$

Time domain analysis provides an intuitive and direct look at the DUT characteristics, and is useful in evaluating the effects of mismatch (discontinuity) in a transmission line. There is also a powerful feature of VNA called time gating data processing that provides the flexibility to selectively remove reflection in the time domain data. These data can be converted back to the frequency domain to be evaluated.

3.1.1 Outline of the Method

An illustration of time gating is shown in Figure 3.1. When measured in the frequency domain, all reflections superpose to present a composite response of all the discontinuities of the DUT. However it is difficult to estimate the relative effects of each of these mismatches. In

contrast when viewing in the time domain, separate responses of each discontinuity as a function of time or distance are easily determined. Using the time gating function of a VNA, a gate is applied to select the response of the mismatch of interest so that only the contribution associated with that discontinuity remains in the measured data. The unwanted time domain responses are reduced by the gate (but not totally removed). The remaining time domain responses can then be transformed back to the frequency domain with the effect of the ‘gated-out’ responses being removed.

Figure 3.1 Process on using VNA time gating function to remove effects of unwanted discontinuities (from Agilent).

Since VNA is only capable of measuring over a finite frequency range, the edge effect causes ringing in the time domain response, which can obscure the smaller responses from the DUT and limit dynamic range of the time domain measurements. A “window” function, which gradually reduces the frequency response and controls the sidelobes created during the truncation process, is applied to frequency domain data prior to conversion to the time domain. Figure 3.2 shows the effect of applying an example window function. The time domain sidelobes are greatly reduced by windowing. However, it also widens the main lobe, thus decreasing the effective resolution. VNA provides different window choices and their effects on main and side lobes are compared in Figure 3.3.

Similar as window, the gating process also involves selecting a gate shape to avoid ripples in the frequency domain. The selection of window and gate functions can have a significant effect on the result. There is also some scaling and renormalization that takes place to ensure the value of the time domain transform retains its physical meaning.

Figure 3.2 Time domain data before and after application of window function. Two plots are with the same scales [75].

Figure 3.3 Window function choices provided by VNA. It shows the window effect on main and side lobes [75].

3.1.2 Measurements Results

Several different flange designs were measured using an Anritsu MS4640A VNA equipped with WM-1295 (140 – 220 GHz or WR-5) frequency extension modules from VDI. The measurement setup is shown in Figure 3.4. A two-port LRL calibration was firstly performed at the reference plane. Measurements were made of reflection coefficient in the frequency domain with time-gating applied at the interface of interest. In the time domain, the gate was used to select the response of the waveguide flange of interest so that only the reflection from that interface remains in the measured data. Similar to earlier worked published by Lau and Denning [28], a gate width of 1 mm with rectangular windowing and minimum gating functions were selected during measurements. Connection repeatability of a pair of flanges was assessed by

measuring the return loss associated with thirteen independent connections and disconnections of the flange.

Figure 3.4 Experimental setup for flange connection repeatability measurements using the time gating technique.

Figure 3.5 shows the gated return loss for thirteen measurements of the original ring-centered flanges using a 1 mm gate width. The return loss is better than 56 dB over the entire frequency band. The variation associated with repeated connections is tightly knitted and superior to the standard UG-387 type as shown in Figure 3.6 (a) and (b). Compared to the results for Lau and Denning design in Figure 3.6 (c), the ring-centered flange has about 15 dB better absolute return loss. As an indication of repeatability, during thirteen connection-disconnection cycles of the ring-centered flange $|S_{11}|$ varied between 0.0007 and 0.0014, a range of 0.0007. Based on Figure 3.6 (c), $|S_{11}|$ for the Lau and Denning flanges varied between 0.0079 and 0.010, a range of 0.002.

However while the ring-centered design appears superior from these results, it cannot be concluded that this will be true in general because return loss and repeatability depend strongly on the dimensional tolerances of the components, which is limited by the precision of the machines used to make them. Ideally, with the identical machining tolerance, performance of Lau-Dening's design should be better than performance of the ring-centered flange, since Lau-Dening design has only two independent components (the raised boss and recessed socket).

Similar measurements were made for the same pair of ring-centered flanges using a wider, 8 mm, gate span as shown in Figure 3.7. The 8 mm width corresponds to close to the half-amplitude time-domain pulse width of the VNA system. The return loss with this gating is better than 45 dB over the entire band.

Figure 3.5 Time gating repeatability results for a pair of original ring-centered waveguide flanges for 13 connection- disconnection cycles in the WM-1295 band, with a 1 mm gate span [40].

(a) Standard UG-387 Flange

(b) Precision UG-387 Flange

(c) Lau-Denning OML Flange

Figure 3.6 Time gating repeatability results in the WM-1295 band from reference [28] for a pair of (a) standard UG-387 flange, (b) precision UG-387 flange, and (c) Lau-Denning flange.

Figure 3.7 Time gating repeatability results in the WM-1295 band for a pair of original ring-centered flange for 13 connection/disconnection cycles, using an 8 mm gate span [40].

3.1.3 Discussion

As discussed in section 3.1.1, there are effects of discrete data sampling, frequency truncation, windowing, gating, and renormalization on the VNA transform process. In order to use time gating technique effectively and extract quantitative information, the user must be aware of its limitations and ambiguities.

The time domain response resolution is defined as the ability to resolve two closely-spaced responses, or a measure of how close two responses can still be distinguished from each other. The gate width selected for time gating measurement should be greater than the response resolution. It is inversely proportional to the frequency span in measurements, and is also related

to the window function applied in the transform. An estimation of the response resolution in free space could be expressed as:

$$\begin{aligned}\text{Response resolution} &= 50\% \text{ impulse width (in time)} \times \text{speed of light} \\ &= k / \text{frequency span} \times \text{speed of light}\end{aligned}$$

where k is a factor representing the relationship between the frequency span and the window selection on response resolution. This can be estimated as in the Table 3-1 [53].

Table 3-1 Approximate relationship between frequency span, window selection and response resolution (k) [53]

Window	Minimum	Normal	Maximum
Bandpass impulse	1.20/frequency span	1.95/frequency span	2.77/frequency span

In our measurements in the WM-1295 frequency band, the response resolution can be calculated and is about 7.3 mm. Figure 3.8 shows example reflections in the time domain for several waveguide sections terminated with waveguide load. Labels showing the approximate widths of 1 mm, 8 mm, and 25 mm are also included in the figure. Clearly the 1 mm gate span is much narrower than the time domain response pulse. Similar time-gating measurements using an 8 mm gate was performed on a pair of ring-centered flanges in the WM-1295 band. Results for reflection coefficient of 13 time disconnection/reconnection cycles are shown in Figure 3.9. As discussed in chapter 1, a waveguide E- or H-plane offset is electromagnetically equivalent to a frequency shunt susceptance at the plane of the interface, thus all reflection coefficient data at

single frequency should move along the constant conductance circle on Smith Chart. However, Figure 3.9 (b) does not agree with our prediction.

Figure 3.8 An example time domain response for several waveguide sections connecting together and terminating with a waveguide load. A few gate widths of 1 mm, 8 mm, and 25 mm are also labeled for comparison.

(a)

(b)

Figure 3.9 Time-gating measurements using an 8 mm gate width for a pair of ring-centered flange in the WM-1295 frequency band. (a) $|S_{11}|$ vs. frequency, and (b) Complex S_{11} on expanded Smith Chart at an example frequency 160 GHz.

3.2 Load-Separation Technique

3.2.1 Outline of the method

An alternative technique for assessing flange repeatability, which does not rely on subtleties associated with VNA's processing of time-gated data, is the load separation method [54]. Measurements are done by first performing a standard one-port calibration (short, offset short, load). The matched termination standard, which is the final standard measured, is then used as a reference against which all subsequent measurements are compared. Repeated measurements of reflection coefficient are taken, connecting and disconnecting the flange of interest (terminated with the matched load standard) to the VNA test port. The resulting complex reflection coefficient plots are a measure of the flange repeatability. Figure 3.10 shows a photograph of our measurement configuration. It should be noted that this technique is done entirely in the frequency domain with no time-gating applied.

Figure 3.10 Measurement schematics for the load-separation technique for flange connection repeatability.

3.2.2 Measurements Results

In this section, we present and discuss measurements of waveguide flange connection repeatability using the load-separation technique for various designs described in chapter 2. These measurements were performed in the 140 – 220 GHz (WM-1295 or WR-5) band, 330 – 500 GHz (WM-570 or WR-2.2) band, and 500 – 750 GHz (WM-380 or WR-1.5) band.

In the WM-380 band, the load-separation technique has been applied to a pair of modified ring-centered flanges and a pair of standard UG-387 flanges. The test system is an Agilent PNAX VNA terminated with VDI frequency modules. Figure 3.11 shows an example of the VNA system stability over time, measured by recording S_{11} for a matched load at two minute intervals over twenty minutes without any disconnection. The data collected shows that the test

system is relatively stable for at least twenty minutes after calibration, and the noise floor is below -60 dB over most of the band. All the following measurements were taken within twenty minutes of calibration to mitigate any effect associated with system drift. All repeatability results have been taken with an IF bandwidth 1 KHz and averaging factor 10, and no smoothing of the data is applied.

Following the load-separation technique, ten connection/disconnection cycles are made for each type of flanges. Return loss as a function of frequency for each measurement is shown in Figure 3.12. And their complex reflection coefficients are shown in Figure 3.13 at an example frequency 675 GHz. For reference, circles of constant return loss 20 dB, 30 dB, and 40 dB are also shown. The first data points, obtained immediately after calibration without disconnecting the matched load, are shown as red points. The other ten black diamonds correspond to ten connection/disconnection cycles. These data suggest that the connection repeatability of the modified ring-centered flanges, characterized using the load-separation technique, is much better than that of the standard UG-387 flanges.

Figure 3.11 The WM- 380 VNA system drifts over twenty minutes after calibration. DUT is a matched load without any disconnection. Data is recorded every two minutes [55].

(a) Modified ring-centered flange

(b) Standard UG-387 flange

Figure 3.12 Repeatability of reflection coefficients measured in the WM-380 band using the load-separation technique for (a) a pair of modified ring-centered flanges, and (b) a pair of standard UG-387 flanges.

(a) Modified ring-centered flanges

(b) Standard UG-387 flanges

Figure 3.13 Complex reflection coefficient measured using the load-separation technique for (a) a pair of modified ring-centered flanges, and (b) a pair of standard UG-387 flanges. Data is shown at 675 GHz. The red point in each plot shows the initial measurement of load standard without disconnection, and the other 10 black diamonds represent 10 connection/disconnection cycles. Note the different scales.

Similar measurements were performed in the WM-1295 and WM-570 band for a pair of modified ring-centered flange (with larger ring), a pair of original ring-centered flange (with smaller ring), and a pair of anti-cocking flanges of the UG-387 type with improved tolerances, similar to the design in [17] but with 0.0625" pin clearance holes. Results for reflection coefficient and experimental standard deviations are presented in Figure 3.14 and Figure 3.15, respectively. The repeatability data indicates, as expected, that the original and modified ring-centered flanges have comparable repeatability, with the points more tightly knit than for the modified UG-387 flange.

The repeatability (experimental standard deviation) for a pair of flanges is also analyzed. For a series of n repeated measurements of the complex-valued reflection coefficient, Γ_i ($i = 1, \dots, n$), a sample mean, $\bar{\Gamma}$, can be defined as:

$$\bar{\Gamma} = \frac{1}{n} \sum_{i=1}^n \Gamma_i$$

And the experimental standard deviation $\sigma(\Gamma)$ is calculated by:

$$\sigma(\Gamma) = \left(\frac{1}{n-1} \sum_{i=1}^n |\Gamma_i - \bar{\Gamma}|^2 \right)^{0.5} \quad (3.1)$$

According to equations (3.1), the experimental standard deviation, $\sigma(\Gamma)$, for a pair of VDI modified UG-387 flange and a pair of original ring-centered flange in the WM-1295 band is calculated and shown in Figure 3.16. The value $\sigma(\Gamma)$ of the original ring-centered flange is much less than that of VDI modified UG-387 flange. The mean $\sigma(\Gamma)$ across the entire frequency band is about 0.0019 for the modified UG-387 flange, and is about 0.0006 for the original ring-centered flange.

In Figure 3.17, the experimental standard deviation of load-separation measurements in the WM-570 band is also calculated base on data shown in Figure 3.15. The mean standard deviation across the frequency band is about 0.0044 for modified UG-387 flange, 0.0017 for modified ring-centered flange, and 0.0010 for original ring-centered flange. It confirms that the repeatability of the modified and the original ring-centered flanges, characterized by the experimental standard deviation, are much superior to that of the modified UG-387 type.

Figure 3.14. The WM-1295 band reflection coefficient measurements using load-separation method for Left: a pair of VDI modified UG-387 flanges [17]; Right: a pair of original ring-centered flanges. The data shown are for (a) 160 GHz, (b) 180 GHz, and (c) 220 GHz. The small hollow circle in each plot shows the initial measurement of load standard without disconnection, and the other 13 points represent 13 connection/disconnection cycles.

(a) Modified Ring-Centered Flange

(b) Original Ring-Centered Flange

(c) Modified UG-387 Flange

Figure 3.15. The WM-570 band S_{11} measurements using load-separation method for (a) modified ring-centered flange, (b) original ring-centered flange, and (c) modified UG-387 flange [17]. Left: $|S_{11}|$ v.s frequency. The lowest data in each plot represents the initial measurement of load standard without any disconnection. Right: complex S_{11} at 425 GHz. Red shows initial measurement. Note the different scales.

Figure 3.16 The WM-1295 band experimental standard deviation of reflection coefficient for VDI modified UG-387 flange [17] and the original ring-centered flange. Calculation is based on data shown in Figure 3.14. The mean standard deviation across the entire frequency band is about 0.0019 for the modified UG-387 flange, and is about 0.0006 for the original ring-centered flange.

Figure 3.17 The WM-570 band experimental standard deviation of reflection coefficient for the modified UG-387 flange [17], the original ring-centered flange, and the modified ring-centered flange. Calculation is based on data shown in Figure 3.15. The mean experimental standard deviation across entire frequency band is about 0.0044 for modified UG-387 flange, 0.0017 for modified ring-centered flange, and 0.0010 for original ring-centered flange.

3.2.3 Gravitational Bias

There was concern that for a horizontally oriented measurement system, the weight of the component under test would tend to pull it downward, introducing a measurement bias that possibly causes a smaller variation in waveguide misalignment during the connection/disconnection cycles than would be expected based solely on dimensional tolerances. As a result,

the spread of repeated measurements might appear smaller than is expected by random alignment. To eliminate the possible gravitational bias, the frequency extender was vertically oriented so the test port surface is perpendicular to the gravitational field, as shown in Figure 3.18. Measurements with this configuration were performed in WM-380 frequency band [55]. System stability over time has been illustrated in previous section in Figure 3.11.

The load-separation repeatability tests were applied to the standard UG-387 flange and three improved designs: the ring-centered interface, and two modified UG-387 flanges. As shown in Figure 3.19, the experimental flange used for these measurements embodies all four designs considered in this section. The modified UG-387 flange is aligned by inserting a single close-fitting dowel into one of the pair of inner holes on the boss directly above and below the waveguide aperture. Alignment was tested with two different sizes of dowel, one smaller than the holes by 0.015 mm in diameter to provide a loose fit, and the other 0.005 mm smaller than the holes in diameter to provide a close fit. In all cases, angular alignment is provided by the flange's outer pins.

Figure 3.18 The WM-380 VNA frequency extension is orientated vertically to overcome gravity effects in flange repeatability tests using the load-separation technique.

Figure 3.19 Photograph of the WM-380 experimental flange. It embodies all four interface designs measured in this section: the standard UG-387 flange, the ring-centered flange, and two modified UG-387 flanges which are aligned by inserting a single close-fitting dowel into one of the pair of inner holes on the boss directly above and below the waveguide aperture.

Load-separation repeatability measurements were performed for the four types of flange using the vertical test system. Ten randomly repeated measurements of reflection coefficient were taken. Also the test load was intentionally forced to its maximum displacement in each cardinal direction (E-plane and H-plane) while tightening the waveguide screws, to produce the worst alignment possible between flanges. The load was also rotated to have the maximum angular misalignment. The connection repeatability of the flange of the termination is characterized by the spread of the resulting data, which are plotted in Figure 3.20 – Figure 3.23 as a function of frequency. Corresponding complex reflection coefficients at representative frequencies of 575 GHz and 675 GHz are shown on the expanded Smith charts in Figure 3.24 – Figure 3.27. For reference, circles of constant return loss are again indicated on each Smith Chart (note the scale differences between diagrams). The initial data points, obtained immediately after calibration without disconnecting the matched load, are shown as filled red points near the center of chart. The other ten data points (filled black diamonds) correspond to ten connection-disconnection cycles. As anticipated, the repeatability of the ring-centered flange and the modified UG–387 flange with the larger alignment dowel, characterized by the spread of the data points, are significantly better than that of the standard UG–387 flange and the modified UG–387 with a smaller alignment dowel.

Electromagnetically, a waveguide misalignment in the E- or H-plane is equivalent to a frequency dependent shunt inductance or capacitance at the plane of the interface as discussed in chapter 1. This is also evident in Figure 3.24 – Figure 3.26, in which most data points line up along y-axis on each expanded Smith Chart. In Figure 3.27, data points line up with certain angle to the y-axis. This is caused by a shift in reference plane during calibration and could be corrected by inputting the precise delay length of delay short standard. However, it should be

noted that all data are related to the initial load measurement without disconnection, and they do not reflect the actual reflection coefficient at the interface.

It is observed that the repeatability data spread on each plot in Figure 3.26 and Figure 3.27, for ring-centered flange and standard UG-387 flange, is relatively larger than that in Figure 3.12-3.13 which was taken on the horizontal test system. The difference confirms the concern that gravity could make flange repeatability results appear better than would be expected from random flange misalignment. With a test system oriented vertically to avoid gravitational bias, more representative measurements of flange repeatability are able to measure using the load-separation technique without gravitational bias.

(a) Ten random connection/disconnection cycles

(b) Intentionally forced the load to its maximum displacement in each direction

Figure 3.20 Repeatability of reflection coefficients measured on vertical test system in the WM-380 band, for the modified UG-387 flange with inner dowels (0.005 mm clearance). The test load has been (a) randomly disconnected/reconnected ten times, and (b) intentionally forced to its maximum possible displacement twice in each direction (waveguide E-plane, H-plane, and rotation). The lower black data in each plot shows initial measurement without disconnection.

(a) Ten random connection/disconnection cycles

(b) Intentionally forced the load to its maximum displacement in each direction

Figure 3.21 Repeatability of reflection coefficients measured on vertical test system in the WM-380 band, for the modified UG-387 flange with inner dowels (0.015 mm clearance). The test load has been (a) randomly disconnected/reconnected ten times, and (b) intentionally forced to its maximum possible displacement twice in each direction (waveguide E-plane, H-plane, and rotation). The lower black data in each plot shows initial measurement without disconnection.

(a) Ten random connection/disconnection cycles

(b) Intentionally forced the load to its maximum displacement in each direction

Figure 3.22 Repeatability of reflection coefficients measured on vertical test system in the WM-380 band, for the improved ring-centered flange. The test load has been (a) randomly disconnected/ reconnected ten times, and (b) intentionally forced to its maximum possible displacement twice in each direction (waveguide E-plane, H-plane, and rotation). The lower black data in each plot shows initial measurement without disconnection.

(a) Ten random connection/disconnection cycles

(b) Intentionally forced the load to its maximum displacement in each direction

Figure 3.23 Repeatability of reflection coefficients measured on vertical test system in the WM-380 band, for the standard UG-387 flange. The test load has been (a) randomly disconnected/reconnected ten times, and (b) intentionally forced to its maximum possible displacement twice in each direction (waveguide E-plane, H-plane, and rotation). The lower black data in each plot shows initial measurement without disconnection.

(a) 575 GHz

(b) 675 GHz

Figure 3.24 Repeatability of complex reflection coefficients measured on vertical test system for the modified UG-387 flange with inner dowels (0.005 mm clearance) at representative frequencies (a) 575 GHz, and (b) 675 GHz. The red point close to center represents the initial measurement without disconnection. Ten black diamonds show ten random connection/disconnection cycles. Four purple diamonds, four green diamonds and two blue diamonds are measurements with the load intentionally pushed towards H-plane, E-plane, and rotational respectively.

(a) 575 GHz

(b) 675 GHz

Figure 3.25 Repeatability of complex reflection coefficients measured on vertical test system for the modified UG-387 flange with inner dowels (0.015 mm clearance) at representative frequencies (a) 575 GHz, and (b) 675 GHz. The red point close to center represents the initial measurement without disconnection. Ten black diamonds show ten random connection/disconnection cycles. Four purple diamonds, four green diamonds and two blue diamonds are measurements with the load intentionally pushed towards H-plane, E-plane, and rotational respectively.

(a) 575GHz

(b) 675 GHz

Figure 3.26 Repeatability of complex reflection coefficients measured on vertical test system for the ring-centered flange at representative frequencies (a) 575 GHz, and (b) 675 GHz. The red point close to center represents the initial measurement without disconnection. Ten black diamonds show ten random connection/disconnection cycles. Four purple diamonds, four green diamonds and two blue diamonds are measurements with the load intentionally pushed towards H-plane, E-plane, and rotational respectively.

(a) 575GHz

(b) 675 GHz

Figure 3.27 Repeatability of complex reflection coefficients measured on vertical test system for the standard UG-387 flange at representative frequencies (a) 575 GHz, and (b) 675 GHz. The red point close to center represents the initial measurement without disconnection. Ten black diamonds show ten random connection/disconnection cycles. Four purple diamonds, four green diamonds and two blue diamonds are measurements with the load intentionally pushed towards H-plane, E-plane, and rotational respectively.

3.2.4 Flange Repeatability with Worst-Case Tolerances

Using the load-separation method, connection repeatability for four candidate flanges (as of June 2012) under consideration by IEEE P1785 group, with the worst-case tolerances, were measured and compared in this section [56]. These results have been presented in the June 2012 IEEE P1785 group meeting.

In these measurements, the dowels and ring were chosen to provide the loosest fit within the design tolerances, thus allowing the worst-case repeatability to be characterized experimentally. Standard UG-387 flanges were also measured for comparison. Measurements were performed in the WM-380 band on a vertical VNA system to avoid gravity bias.

As shown in Figure 3.28, four candidates are examined in this section:

- 1) Precision UG-387 interface A1, as shown in Figure 3.28 (a). A pair of inner holes of equal size are located in the E-plane. Alignment is provided by two inner dowels of different sizes: a larger close-fitting dowel D1 provides lateral alignment and a smaller loose-fitting dowel D2 controls the angular orientation of the flanges.
- 2) Precision UG-387 interface A2, as shown in Figure 3.28 (b). A pair of inner holes of equal size are located in the E-plane, identical to those of A1. Alignment is provided by two equal sized inner dowels. Two versions of A2 interface are under consideration: A2-a using a pair of identical dowels of the largest possible diameter, and A2-b using a pair of dowels identical to the smaller dowel (D2) of interface A1.
- 3) Precision UG-387 interface A3, as shown in Figure 3.28 (c). A pair of inner holes of equal size are located in the E-plane. Alignment is provided by one close-fitting inner

dowel to provide lateral alignment, and the outer UG-387 pins which control the angular orientation.

- 4) The ring-centered flange, as shown in Figure 3.28 (d). Alignment of the ring-centered flange depends on the coupling ring which is a close fit on the central bosses. A relatively loose outer pin provides angular alignment.

To make a fair comparison between the repeatability of the different flange types, a pair of experimental waveguides were fabricated with flanges embodying all the designs listed above. A photograph and mechanical drawing of the flange made by VDI are shown in Figure 3.29. These waveguide pieces can accommodate all required sizes of alignment dowels, as well as a boss coupling-ring. To simulate the worst case situation, the hole and boss diameters of the actual flanges were measured accurately using gage pins and gage rings, then pins and rings with appropriate diameters were chosen to give the worst case clearances. The measured dimensions of the experimental components are listed in Table 3-2. (Note that position errors in fabricating the flanges were not considered here.)

(a) Interface A1. Two unequal inner dowels.

(b) Interface A2. A2-a: largest possible equal size inner dowels; A2-b: Inner dowels both equal to D2 of A1.

(c) Interface A3. Close fitting dowel D and loose pin P.

(d) Ring-centered flange. Close fitting coupling ring and loose pin P.

Figure 3.28 Flange standard candidates considered in this section. Filled circles indicate the dowels and holes used for alignment.

(a) Photography

(b) Mechanical drawing

Figure 3.29 (a) Photograph and (b) mechanical drawing of the WM-380 experimental waveguide flange used in this section.

Table 3-2
Dimensions of Flanges Components

'Precision' UG-387 Flanges	Inner Holes Dia. (mm)	Inner Dowel Dia. (mm)
A1	1.570 (61.80 mils)	D1=1.562 (61.50mils)
		D2=1.552 (61.10mils)
A2-a	1.570 (61.80 mils)	D=1.557 (61.30mils)
A2-b	1.570 (61.80 mils)	D=1.552 (61.10mils)
A3	1.570 (61.80 mils)	D=1.562 (61.50mils)

	Boss Dia. (mm)	Ring Dia. (mm)
Ring-Centered Flange	9.520 (374.80 mils)	9.530 (375.20 mils)

* All dimensions have 0.5 μm (0.020 mil) tolerance.

Connection repeatability for each type of flange was measured using the load-separation technique on a Rhode and Schwartz ZVA40 VNA with VDI WM-380 frequency extension modules. The test port is vertically oriented to eliminate gravity effects which we have discussed in the previous section.

Following the load-separation method, ten independent connection/disconnection cycles were made for the ‘precision’ UG-387 flanges, ring-centered flanges, and standard UG-387 flanges. In addition, measurements were taken with the flanges intentionally pushed to their maximum displacement in each direction (E-plane, H-plane and rotation) while tightening the screws, to produce the worst-case alignment possible between flanges. The magnitude of the reflection coefficient of ten connection/disconnection cycles for these flanges as a function of frequency is shown in part (a) of Figures 3.30 – 3.35. For the "pushed" assemblies, two measurements were recorded and are plotted in part (b) of Figures 3.30 – 3.35. Again, the lowest traces in (a) and (b) are the first measurements immediately after calibration, without any disconnection. The corresponding complex reflection coefficients are also plotted on Smith Charts at a representative frequency of 625 GHz, as shown in part (c) of Figure 3.30 – 3.35. In each plot, the pink, green, and light blue diamonds are measurements with the flanges pushed in the H-plane, E-planes, and rotation, respectively, while tightening the screws. The ten black dots represent the connection/disconnection data. And the red dot is the initial measurement before disconnection of the load. It is clear from these data that the ‘precision’ UG-387 A1 flange and the ring-centered flange exhibit the best repeatability compared to the other designs.

Figure 3.36 shows the experimental standard deviation as a function of frequency for the different flanges, for ten connection/disconnection measurements. The experimental standard deviation is calculated according to equations (3.1). Tables 3-3 summarizes the minimum, maximum, and mean experimental standard deviation across the WM-380 frequency band.

(a) $|S_{11}|$ measured for ten disconnection/reconnection cycles.

(b) $|S_{11}|$ measurements with the flanges pushed in the indicated direction while tightening the screws.

(c) Complex S_{11} on a Smith Chart at 625 GHz.

Figure 3.30 Reflection coefficient of the precision UG-387 A1 flange with worst-case tolerance in the WM-380 band.

(a) $|S_{11}|$ measured for ten disconnection/reconnection cycles.

(b) $|S_{11}|$ measurements with the flanges pushed in the indicated direction while tightening the screws.

(c) Complex S_{11} on a Smith Chart at 625 GHz.

Figure 3.31 Reflection coefficient of the precision UG-387 A2-a flange with worst-case tolerance in the WM-380 band.

(a) $|S_{11}|$ measured for ten disconnection/reconnection cycles.

(b) $|S_{11}|$ measurements with the flanges pushed in the indicated direction while tightening the screws.

(c) Complex S_{11} on a Smith Chart at 625 GHz.

Figure 3.32 Reflection coefficient of precision UG-387 A2-b flange with worst-case tolerance in the WM-380 band.

(a) $|S_{11}|$ measured for ten disconnection/reconnection cycles.

(b) $|S_{11}|$ measurements with the flanges pushed in the indicated direction while tightening the screws.

(c) Complex S_{11} on a Smith Chart at 625 GHz.

Figure 3.33 Reflection coefficient of precision UG-387 A3 flange with worst-case tolerance in the WM-380 band.

(a) $|S_{11}|$ measured for ten disconnection/reconnection cycles.

(b) $|S_{11}|$ measurements with the flanges pushed in the indicated direction while tightening the screws.

(c) Complex S_{11} on a Smith Chart at 625 GHz.

Figure 3.34 Reflection coefficient of ring-centered flange with worst-case tolerance in the WM-380 band.

(a) $|S_{11}|$ measured for ten disconnection/reconnection cycles.

(b) $|S_{11}|$ measurements with the flanges pushed in the indicated direction while tightening the screws.

(c) Complex S_{11} on a Smith Chart at 625 GHz.

Figure 3.35 Reflection coefficient of the standard UG-387 flange in the WM-380 band. Note the different scale in part (c) than in previous Smith Chart plots.

Figure 3.36 Experimental standard deviation of S_{11} for ten connection/disconnection cycles of the flanges with the worst-case tolerances in the WM-380 band.

Table 3-3**Experimental Standard Deviation of Reflection Coefficients of WM-380 Flanges**

Flange	Experimental Standard Deviation (Linear)					
	Min.	Max.	Average	500GHz	625GHz	750GHz
A1	0.0110	0.0223	0.0144	0.01205	0.013051	0.021238
A2-a	0.0156	0.0311	0.2020	0.016033	0.018391	0.029966
A2-b	0.0237	0.0560	0.0355	0.025611	0.029997	0.052564
A3	0.0103	0.0193	0.0131	0.019072	0.011141	0.013879
Ring-Centered	0.0076	0.0226	0.0125	0.008695	0.011042	0.020419
Standard UG-387	0.1236	0.2793	0.1762	0.132524	0.162694	0.244095
System drift over 20	0.0000591	0.0015	0.000272	0.001492	0.000346	0.000492

3.2.5 Discussion

Measurements of the reflection coefficient in Figure 3.30 – Figure 3.35 can be noticed to be worse than their predicted worst-case reflection coefficients. The reason behind this issue is that the load-separation technique compares all subsequent connection data to the initial measurement without disconnection but it does not indicate the absolute reflection coefficient at the interface. Results using load-separation method could be significantly biased if the initial connection of the matched termination standard has a relatively large misalignment. This is difficult to observe when plotting repeatability results in the format of return loss versus frequency, but is obvious on the polar plots of the reflection coefficients. For example, if the matched termination standard is offset relative to the waveguide E- or H-plane, all subsequent data will have an additional shunt inductance or capacitance artifact produced from the calibration. As a result, data points are less evenly distributed along a curve of the constant susceptance on the smith chart relative to the center of chart.

A series of Monte-Carlo simulation were performed to explore this issue and the results are shown in Figure 3.37. A simulation of misaligned WM-380 waveguides was created containing one-dimension E-plane or H-plane misalignments. 1000 samples were generated from a normal distribution with limits of 25.4 μm (1 mil) in each direction, using a program currently being developed in P1785 group [57]. Figure 3.37(a) assumes the match standard used during calibration is perfect and shows the distribution of complex reflection coefficients on smith chart at 625 GHz. Figure 3.37(b) shows the biased distribution produced when the match termination standard has its worst-case offset in the waveguide E-plane. In this figure, it can be seen that all data exhibit an additional shunt inductance. As shown in Figure 3.37(c), this bias could be

reduced by using the average of all connections as the match standard. However it cannot be totally eliminated because the effects of waveguide misalignment in the E- and H-plane are not symmetric. Reflection from a waveguide E-plane offset is usually more severe than from an H-plane offset. Note these simulations are generated from normalization without performing the entire calibration process, but it is a valid approximation assuming that the error network is small.

In addition, the load-separation raw data from Figure 3.30 was re-calibrated for a pair of ‘precision’ UG-387 A1 flanges with the worst-case tolerance, by applying different match standard data during calibration. As shown in Figure 3.38, the match termination standard is chosen as the maximum misaligned data in the E-plane, the maximum misaligned data in the H-plane, and the average of ten random connection/disconnection measurements, respectively. Data for the short and delay short standards remains the same. From these complex reflection coefficient plots, we see that the difference in repeatability results by using various match termination standards could be as much as 8 dB. Thus when comparing different flanges’ repeatability using the load-separation technique, it is important to keep relatively consistent on alignment of the match termination standard. Averaging over several connections is recommended, but does not eliminate the bias.

(a) Match standard is perfect

(b) Match standard has the worst-case offset in the E-plane

(c) Match standard is the average of all samples

Figure 3.37 Monte-Carlo simulation on a pair of WM-380 waveguides with E- or H-plane misalignment. 1000 samples were generated from normal distribution with limits of 25.4 μm (1 mil) in each direction. Results show the complex S_{11} at 625 GHz. Data is normalized to (a) a perfect match standard ($\Gamma=0$); (b) a match standard with worst-case offset in the E-plane; and (c) the average of all samples. All plots are in the same scale.

(a) Match standard has the worst-case offset in the E-plane

(b) Match standard has the worst-case offset in the H-plane

(c) Match standard is the average of the ten random connection/reconnection cycles

Figure 3.38 The WM-380 band load-separation measurements for ‘precision’ UG-387 A1 flange with the worst-case tolerance. Raw data is the same as in Figure 3.30. But calibration is different by using (a) a match standard with worst-case offset in the E-plane; (b) a match standard with worst-case offset in the H-plane; and (c) a match standard which is the average of ten random disconnection/ reconnection measurements. Results show the complex S_{11} at 625 GHz.

Chapter 4

Absolute Flange Misalignment

4.1 Introduction

The load-separation technique discussed so far has been well-suited for flange connection repeatability measurements. It characterizes the precision of waveguide flange. However, all data are related to the initial load measurement without disconnection, and they do not indicate the actual reflection coefficient at the interface.

Absolute measurement of the reflection coefficient of a pair of waveguide flanges is generally difficult at submillimeter frequency range. For well-aligned flanges the reflection is very small, and to measure it a calibration method is needed which is not affected by flange misalignments of the same order as those being characterized. Also, it requires either a matched termination of return loss greater than that of the interface being measured or an alternative standard with an accurately known complex reflection coefficient. As a result, little work has been published on measurements of absolute flange misalignment at high frequencies.

In this chapter, we will use a new calibration technique which is insensitive to waveguide misalignment to characterize flange misalignment. This technique uses four standards, including a flush short, two delay shorts with unspecified but different phases, and a radiating open waveguide (this calibration is denoted as SDD(RO)). The concept of this calibration method has been previously published by Liu and Weikle [58], however the calibration has not been applied to measurements at submillimeter wavelengths. This chapter begins with analysis of accuracy and precision of this calibration method. Due to the scarcity of verification standards for frequencies above 325 GHz, accuracy of calibration is evaluated by comparing the measured and ideal reflection coefficients of several delay shorts. To further investigate the precision of SDD(RO) calibration method, experimental uncertainty of the calibration is compared with connection repeatability for several different types of flange designs. Finally, we apply this calibration to measure the true reflection coefficient for waveguide flanges with various terminations, including a radiating waveguide shim, a milled quarter-wave delay short, and a near-matched waveguide load. All measurements are performed in the WM-380 (WR-1.5 or 500 – 750 GHz) frequency band.

4.2 Calibration Method Insensitive to Flange Misalignment

Waveguide flange misalignment, resulting from the limited precision of waveguide machining techniques, can introduce substantial uncertainty in calibration standards, such as waveguide matched loads, delay shorts, and straight waveguide lines. It has long been recognized as a significant limitation of the calibration accuracy of VNAs at millimeter and

submillimeter-wave frequencies [59] [60]. The most common calibration methods currently used for VNAs are subject to this problem and are not suitable for characterizing the small reflection coefficient from a pair of waveguide flanges.

A one-port VNA calibration technique insensitive to flange misalignment was proposed in 2006 [58]. This method (denoted as SDD(RO)) consists of four calibration standards: a flush short, two delay shorts with unspecified but different phases, and a radiating open waveguide. The short circuit and radiating open is not susceptible to flange misalignment. Also, because the exact knowledge of the phases associated with two delay shorts are not required and their magnitudes are assumed to be unity, this calibration mitigates phase errors associated with misaligned delay shorts. None of the four standards suffer from waveguide misalignment, thus the calibration overall is insensitive to flange misalignment and could be applied to measure the true reflection coefficient from a pair of flanges.

4.2.1 Calibration Analysis

For one-port VNA calibration, it is well known that relationship between the actual (Γ) and measured (ω) reflection coefficient is bilinear:

$$\Gamma = \frac{B - \omega}{C\omega - A} \quad (4.1)$$

where A, B, and C are three error terms to be determined by measuring three known standards that yield three simultaneous equations. These three equations can then be solved for the three error terms.

In the SDD(RO) calibration method, four standards are included: short, two delay shorts, and load (radiating open-ended waveguide). Exact knowledge of the phases associated with the delayed shorts is not required. Thus error terms A, B, and C can be solved by the following four equations:

$$-1 = \frac{B - \omega_s}{C\omega_s - A} \quad (\text{Short}) \quad (4.2)$$

$$1 = \left| \frac{B - \omega_1}{C\omega_1 - A} \right| \quad (\text{Delay Short 1}) \quad (4.3)$$

$$1 = \left| \frac{B - \omega_2}{C\omega_2 - A} \right| \quad (\text{Delay Short 2}) \quad (4.4)$$

$$\Gamma_L = \frac{B - \omega_L}{C\omega_L - A} \quad (\text{Load}) \quad (4.5)$$

where Γ_L is the complex reflection coefficient of arbitrary known load, and here it refers to radiating open-ended waveguide.

Term A can be expressed by an expression of B and C from (4.2):

$$A = B - \omega_s + \omega_s C \quad (4.6)$$

Then (4.3) – (4.5) become:

$$1 = \left| \frac{B' - \omega_1'}{C\omega_1' - B'} \right| \quad (4.7)$$

$$1 = \left| \frac{B' - \omega_2'}{C\omega_2' - B'} \right| \quad (4.8)$$

$$\Gamma_L = \frac{B' - \omega_L'}{C\omega_L' - B'} \quad (4.9)$$

where $\omega_1' = \omega_1 - \omega_s$, $\omega_2' = \omega_2 - \omega_s$, $\omega_L' = \omega_L - \omega_s$, and $B' = B - \omega_s$.

Geometrically, equation (4.7) describe a circle on complex C -plane, with center at $\frac{B'}{\omega_1'}$ and radius $\left| \frac{B'}{\omega_1'} - 1 \right|$. Similarly equation (4.8) represents another circle on complex C -plane, with center at $\frac{B'}{\omega_2'}$ and radius $\left| \frac{B'}{\omega_2'} - 1 \right|$. As illustrated in Figure 4.1, there are two intersection points between two circles: one is $C = 1$, and the other gives solution of C as explicit function of B' . Detailed algorithm on solving the intersection point can be found in reference [58].

Finally, by substituting the expression of C as function of B' into equation (4.9), the complex B' could be solved explicitly. Then all the three calibration error coefficients A , B , and C are determined.

Figure 4.1 Geometrical solutions of equations (4.7) and (4.8). They represent two intercepted circles on the complex C -plane [58].

4.2.2 Radiating Open-Ended Waveguide Standard

Radiating open-ended waveguide has been studied by several groups and has found broad applications in near-field and anechoic antenna measurements, as phased-array elements, and also in materials measurements [61] [62] [63]. There are different ways to estimate the actual reflection coefficient of an open-ended rectangular waveguide. A numerical solution can be found by simulation in HFSS with a rectangular aperture in a flat, infinite conducting plane. Complete simulation in HFSS, including waveguide flange details (pins, holes, and boss) and actual dimension, is difficult at submillimeter frequencies because the problem size becomes too large for most computers today. An approximate, analytical form using fitted Legendre coefficients for the reflection coefficient of radiating open-ended waveguide has also been described in [64] and this paper examines as well the impact of finite flanges and burrs.

Also, an EMF analysis technique can be applied to determine the reflection coefficient of radiating open-ended waveguide [16] [65]. Representing the waveguide aperture field as equivalent magnetic current and applying Poynting's Theorem, the expression for the driving-point admittance of the aperture can be found as:

$$Y = \frac{-1}{|V|^2} \iint \vec{H} \bullet \vec{M}^* dx dy = -\frac{1}{|V|^2} \iint_{\infty} \{Y_{TM} |M^{TM}(k_x, k_y)|^2 + Y_{TE} |M^{TE}(K_x, K_y)|^2\} dk_x dk_y \quad (4.10)$$

where M^{TM} and M^{TE} are magnetic current distributions for the transverse magnetic (TM) and transverse electric (TE) modes, respectively.

$$M^{TM}(k_x, k_y) = \left\langle \vec{M}(x, y) \left| \hat{u}_{TM} \right. \right\rangle = \iint_{Aperture} \vec{M}(x, y) \bullet \hat{u}_{TM}^* dx dy \quad (4.11)$$

$$M^{TE}(k_x, k_y) = \left\langle \vec{M}(x, y) \left| \hat{v}_{TE} \right. \right\rangle = \iint_{Aperture} \vec{M}(x, y) \bullet \hat{v}_{TE}^* dx dy \quad (4.12)$$

where $\hat{u}_{TM}$ and $\hat{v}_{TE}$ are the unit TM and TE vectors, respectively.

Assuming only the TE₁₀ mode exists in the rectangular waveguide, the magnetic current can be expressed as:

$$\vec{M}(x, y) = \hat{x} M_0 \cos\left(\frac{\pi x}{a}\right), \quad -\frac{a}{2} \leq x \leq \frac{a}{2}, \text{ and } -\frac{b}{2} \leq y \leq \frac{b}{2} \quad (4.13)$$

where a and b are rectangular waveguide's width and height.

By substituting (4.13) into (4.11), (4.12) and (4.10), the structure admittance is then given as:

$$Y = -\frac{1}{|V|^2} \iint_{-\infty}^{\infty} \frac{(M_0 b)^2}{a^2 \eta} \text{sinc}^2\left(\frac{k_y b}{2}\right) \left[\frac{\cos\left(\frac{k_x a}{2}\right)}{\left(\frac{\pi}{x}\right)^2 - k_x^2} \right]^2 \times \left[\frac{k_y^2}{k_c^2} \times \frac{1}{\sqrt{1 - \left(\frac{k_c}{k}\right)^2}} + \frac{k_x^2}{k_c^2} \sqrt{1 - \left(\frac{k_c}{k}\right)^2} \right] dk_x dk_y \quad (4.14)$$

where $\eta = \sqrt{\frac{\mu}{\varepsilon}}$. Note that $M_0 b = V$ is the voltage measured across center of the waveguide.

Let $k_c = \beta$, $k_x = \beta \cos \phi$, $k_y = \beta \sin \phi$, equation (4.14) can be written as:

$$Y = \int_0^{\infty} \int_0^{2\pi} \frac{1}{a^2 \eta} \text{sinc}^2\left(\frac{\beta b}{2} \sin \phi\right) \left[\frac{\cos\left(\frac{\beta a}{2} \cos \phi\right)}{\left(\frac{\pi}{x}\right)^2 - \beta^2 \cos^2 \phi} \right]^2 \times \left[\frac{\sin^2 \phi}{\sqrt{1 - \left(\frac{\beta}{k}\right)^2}} + \cos^2 \phi \sqrt{1 - \left(\frac{\beta}{k}\right)^2} \right] \beta d\beta d\phi \quad (4.15)$$

Equation (4.15) can then be explicitly calculated using computer calculator, such as MathCAD. For WM-380 (WR-1.5 or 500-750 GHz) rectangular waveguide with 2:1 ratio, the reflection coefficient of radiating open-ended waveguide calculated using above EMF method is shown in Figure 4.2. For a comparison, result from HFSS simulation with a rectangular aperture in a flat, infinite conducting plane is also plotted. Reflection coefficients of radiating open-ended waveguide from EMF calculation and HFSS simulation are similar in the entire frequency band, with an about 0.02 linear difference (-34 dB).

To further verify the SDD(RO) calibration uncertainty associated with using different models of calibration standards, a WM-380 precision waveguide load from VDI was measured and data was corrected by applying different models of radiating open standard from HFSS simulation and EMF calculation, respectively. Calibrated reflection coefficient of this precision waveguide load is shown in Figure 4.3. It shows that there is about 3 dB difference in magnitude of reflection coefficient corrected using calibration with two different radiating open models. Return loss of VDI precision waveguide load should be better than the 20 dB shown in our measurements, and we will address this issue later in section 4.3.3 in this chapter.

Figure 4.2 Actual complex reflection coefficient of WM-380 (500-750 GHz) radiating open-ended waveguide. Results are calculated using EMF analysis technique and numerical solution in HFSS simulator, respectively.

(a) Magnitude of reflection coefficient

(b) Phase of reflection coefficient

Figure 4.3 Reflection coefficient of a WM-380 precision waveguide load calibration by using SDD(RO) method with different models of radiating open standard from Figure 4.2.

4.2.3 Calibration Performance

Performance of the SDD(RO) calibration method has also been evaluated in the WM-380 band (500-750 GHz). Two waveguide delay lines, of nominal lengths ~ 92 and ~ 160 μm , were used but exact knowledge of the length of the lines is not needed for calibration. A radiating open-ended waveguide is used as the fourth standard and its actual reflection coefficient is simulated in HFSS with a rectangular aperture in a flat, infinite conducting plane.

Due to the scarcity of verification standards for frequencies above 325 GHz, accuracy of calibration is evaluated by comparing the measured and ideal reflection coefficients of several delay shorts, including the two delay short standards and also a milled delay short of nominal length ~ 140 μm . Ideal performance of delay short is simulated in HFSS calculator.

Figure 4.4 shows the phases of the reflection coefficient of the two delay shorts corrected using SDD(RO) calibration algorithm. The nominal phases simulated from the waveguide dimensions are also shown as dashed lines. The difference between measured and theoretical phases is within $\pm 3^\circ$ across the full band for both delay shorts.

Figure 4.5 shows measurements for reflection coefficient of a milled $\lambda/4$ delay short corrected using SDD(RO) calibration, and compares with its theoretical values simulated from the waveguide dimensions. Corrected return loss is about 0.02 dB for most of the frequency band, and the peak at 557 GHz is caused by a water vapor line. Measured and simulated phases are in excellent agreement in entire frequency band.

Also, we attempted to examine the SDD(RO) calibration using two delay short standards of similar phases. Their nominal delay lengths are ~ 132 μm and ~ 166 μm , respectively. Figure 4.6 shows corrected phases of reflection coefficient of the two delay shorts, and compares with their

theoretical values. Phases of these two delay short standards are still in quite good agreement with simulations. This suggests that the SDD(RO) calibration works even when the two delay short standards have relatively close phases.

(a) 92 μm delay short standard

(b) 160 μm delay short standard

Figure 4.4 Measured and simulated phases of reflection coefficients for two delay shorts standards (of nominal delay lengths 92 μm and 160 μm). Measurements are corrected using SDD(RO) calibration.

(a) Magnitude of reflection coefficient

(b) Phase of reflection coefficient

Figure 4.5 Measured and simulated reflection coefficients for a milled $\lambda/4$ delay short (of nominal length $\sim 140 \mu\text{m}$). Measurements are corrected using SDD(RO) calibration.

Figure 4.6 Measured and simulated phases of reflection coefficients for two delay shorts standards of close phases. One of them has nominal delay lengths $\sim 132 \mu\text{m}$ and the other is $\sim 166 \mu\text{m}$. Measurements are corrected using SDD(RO) calibration.

To further investigate the precision of SDD(RO) calibration scheme, a repeatability exercise is performed by applying different calibrations to correct the measurement of a single DUT (a waveguide load in the WM-380 band). The procedure first records the uncorrected reflection coefficient of each calibration standard (short, two delay shorts, and radiating open-ended waveguide) three times, with the standard being disconnected and reconnected each time. A total of 81 different VNA error networks can be generated from the different combinations of measurements of the four calibration standards. By applying all permutations of the error

networks to the same DUT measurement, the standard deviation across calibrations at each frequency can be found. This provides an estimate of uncertainty of the calibration scheme.

The standard deviation is calculated in following way. For a series of n repeated measurements of the complex-valued reflection coefficient, Γ_i ($i = 1, \dots, n$), a sample mean, $\bar{\Gamma}$, can be defined as:

$$\bar{\Gamma} = \frac{1}{n} \sum_{i=1}^n \Gamma_i$$

And the experimental standard deviation $\sigma(\Gamma)$ is calculated by:

$$\sigma(\Gamma) = \left(\frac{1}{n-1} \sum_{i=1}^n |\Gamma_i - \bar{\Gamma}|^2 \right)^{0.5} \quad (4.16)$$

Figure 4.7 shows the uncertainty of the SDD(RO) calibration based on the above procedure (lowest black curve) and compares it with the standard deviation of measurements repeated 20 times on the four different flange types. All measurements were taken with the same load as the DUT (the waveguide pieces are made with compound flanges fully compatible with all four of the interface types being evaluated). The measurements on each flange type were corrected using the same error network which is randomly chosen among the 81 possible error networks. The standard deviation is then calculated across the corrected 20 measurements at each frequency. As expected, the standard deviation is lowest for the SDD(RO) calibration uncertainty, and highest for the standard UG-387 flange. It suggests that the measurement uncertainty associated with the SDD(RO) calibration is less significant than that of the flange repeatability connection error.

Furthermore, the SDD(RO) method assumes magnitude of reflection coefficient of two delay short standards is unity, as shown in equation (4.3) and (4.4). However, there is loss in waveguide and junction. To investigate effect of loss, measurements are corrected using

SDD(RO) method assuming loss in delay short standards. Figure 4.8 shows phases of reflection coefficient for two delay short standards in the MW-380 band, when no loss ($|S_{11}| = 1$), 0.05 loss ($|S_{11}| = 0.95$), or 0.10 ($|S_{11}| = 0.90$) loss is included in SDD(RO) calibration method. The theoretical phase is calculated using their actual delay lengths. Results suggest that a 0.05 loss of delay short standards can introduce about 2° phase error. Figure 4.9 shows magnitude of reflection coefficient of a WM-380 precision waveguide load corrected using SDD(RO) method when both delay short standards have no loss ($|S_{11}| = 1$) or 0.10 loss ($|S_{11}| = 0.90$), respectively. It shows about 2 dB difference in return loss of compared to a calibration assuming lossless standards.

Figure 4.7 Comparison of measured-based uncertainty from SDD(RO) calibration, uncertainty from flange connections for standard UG-387 flange, modified UG-387 flanges, and ring-centered flange in the WM-380 band. The same DUT (a precise waveguide load in WM-380 band) and the same calibration technique SDD(RO) are applied for all measurements.

(a) Phases of the 92 μm delay short standard

(b) Phases of the 160 μm delay short standard

Figure 4.8 Phases of two delay short standards of nominal length (a) 92 μm and (b) 160 μm corrected using SDD(RO) method, when the two delay short standards are lossless or lossy ($|S_{11}|=0.95$ or $|S_{11}|=0.90$), respectively. Theory phases calculated from actual delay lengths are also plotted in red dashed lines for comparison.

Figure 4.9 $|S_{11}|$ of a WM-380 precision waveguide load corrected using SDD(RO) method, when the two delay short standards are lossless or lossy ($|S_{11}|=0.90$), respectively.

4.3 Absolute Flange Mismatch Measurements

Direct measurement of the reflection coefficient of a pair of waveguide flanges is difficult, for it requires a calibration that is insensitive to flange misalignment and a matched termination of return loss greater than that of the interface being measured (or an accurately known load). The SDD(RO) calibration discussed in the previous section is a good choice because it does not rely on flange alignment and the uncertainty associated with this method is smaller than that of

the flange. We now apply this method to characterize the reflection from a pair of misaligned flanges.

In this section, the SDD(RO) calibration is applied and the flange mismatch is measured with three different terminations connected to the test port, a radiating waveguide shim, a quarter-wave delay short, and a waveguide load, respectively.

4.3.1 Radiating Shim Termination

Measurements are first performed with a waveguide shim radiating into an infinite half space. Because the radiating open-ended waveguide does not suffer from waveguide misalignment, it is useful as a termination for quantitative measurements on flange misalignment. In addition, the actual physical flange misalignment is observable under a microscope when terminated with the radiating open-ended waveguide. This allows the measured return loss to be correlated with the physical offset of the waveguides.

During the measurements, a thin waveguide shim of nominal length $\sim 180\text{ }\mu\text{m}$, terminated in a radiating open, is connected to the VNA test port. As shown in Figure 4.10, the VNA frequency extender is vertically mounted, so the shim can sit stably on the test port. A normal force is applied by pressing down on the shim to flatten it and eliminate any air gap between shim and test port. A piece of eco foam of dielectric constant 1.04 is used between the shim and fingers. A microscope above the test port allows offsets between the shim and the test port to be observed and measured using a microscope reticle. The shim waveguide has rounded corners and its dimensions were chosen to provide a first-order match to the adjoining rectangular waveguide [66]. Because the radiating open is not connected to a waveguide, the only flange misalignment

is at the interface of the shim and test port. An SDD(RO) calibration is first performed as usual using a flush short, two delay shorts of nominal lengths 92 μm and 160 μm , and a radiating open-ended waveguide. Reflection coefficient measurements are then performed when the shim and test port are well-aligned visually and then when the shim is intentionally moved in one direction to produce a deliberate misalignment along waveguide E- or H-planes. Figure 4.11 illustrates the waveguide misalignment observed under microscope between test port flange and shim. The misalignments were measured using a microscope reticle to be $\delta x = 32.5 \pm 6.5 \mu\text{m}$ (H-plane) and $\delta y = 26 \pm 6.5 \mu\text{m}$ (E-plane).

Figure 4.10 VNA system setup for measuring actual flange mismatch terminated with a radiating waveguide shim. The frequency extender is vertically mounted, so the shim can sit stably on the test port. A microscope above the test port allows offsets between the shim and the test port to be observed and measured using a microscope reticle.

Figure 4.11 Photos of flange misalignment between test port and shim observed using a microscope reticle. The shim has been intentionally moved in one direction to produce a deliberate misalignment along (a) waveguide H-plane ($\delta x = 32.5 \pm 6.5 \mu\text{m}$), and (b) waveguide E-plane ($\delta y = 26 \pm 6.5 \mu\text{m}$).

Figure 4.12 shows the measured reflection coefficient of the radiating shim in the complex plane. The plot includes reflection coefficient when the shim and test port flanges are close-to-perfectly aligned as observed under microscope, and when the shim is purposely pushed to one end, causing a misalignment in waveguide H- or E-plane, respectively.

According to electromagnetic study, applying an H-plane waveguide offset introduces a frequency dependent shunt inductance at the plane of waveguide junction, whereas applying an E-plane misalignment causes a frequency dependent shunt capacitance. The equivalent shunt susceptance can be estimated from Harrington's formulas [16]:

$$B_L = -\frac{4\lambda}{\eta\pi^2 b} \left(\frac{c}{a}\right)^2 \sum_{m=2}^{\infty} \left[\frac{\sin\left(\frac{m\pi c}{a}\right)}{1 - \left(\frac{mc}{a}\right)^2} \right]^2 \sqrt{\left(\frac{m}{2}\right)^2 - \left(\frac{a}{\lambda}\right)^2} \quad (\text{for H - plane waveguide offset}) \quad (4.17)$$

$$B_c = \frac{4a}{\lambda_g Z_0} \sum_{n=0}^{\infty} \frac{\sin^2\left(\frac{n\pi c}{b}\right)}{\left(\frac{n\pi c}{b}\right)^2 \sqrt{n^2 - \left(\frac{2b}{\lambda_g}\right)^2}} \quad (\text{for E - plane waveguide offset}) \quad (4.18)$$

where a and b are rectangular waveguide width and height dimensions, and c is the overlap width (or height) between two jointing waveguides. λ_g and Z_0 are guided wavelength and characteristic impedance of the dominant mode TE_{10} .

By substituting the microscope measured physical waveguide misalignment values into above formulas, the equivalent shunt susceptance introduced by H- or E-plane offset can be analytically calculated. Figure 4.13 compares measurements in Figure 4.12 and their theoretical performance by adding an equivalent shunt inductance or shunt capacitance at the flange jointing interface. In figure 4.13(a), the measured reflection coefficient when the shim is misaligned in the H-plane is compared with the well-aligned measurements connected by adding a shunt inductance at the reference plane. Similarly, Figure 4.13(b) compares the measured reflection coefficient when the shim has an offset in the E-plane with the well-aligned measurements corrected by adding a shunt capacitance at the reference plane. Note that there are no fitted parameters here. The offsets used in formulas (4.17) and (4.18) are those measured values using the microscope. Measurements and analytical formulas for waveguide offsets in H- or E-plane are in quite good agreement. Furthermore, by terminating with radiating open, this experiment has permitted the electrical response and flange offset to be correlated and compared.

Figure 4.14 compares reflection coefficient of measurement and simulation of the radiating shim without flange misalignment. Measurement is corrected using SDD(RO) method with different radiating open models generated using HFSS and EMF method (as shown in Figure

4.2), respectively. Measurement and simulation are in similar shape. The discrepancy may be caused by effect of flange details in radiating open simulation, effect of loss in delay short standards, effect of waveguide misalignment between test port and shim included in measurement, etc. The HFSS model of radiating open is used through the following sections.

Figure 4.12 Measured reflection coefficient for a waveguide shim (of nominal length 180 μm) terminated with open-ended waveguide over the frequency range of 500 GHz – 750 GHz. Measurements include reflection coefficient when the shim and test port flanges are close-to-perfectly aligned (as observed under microscope), and when the shim is purposely pushed to one end, causing a misalignment in waveguide H- or E-plane, respectively. Results are plotted on complex plane.

(a)

(b)

Figure 4.13 Comparison of measured and simulated complex reflection coefficient for the shim terminated with open-ended waveguide over the frequency range of 500 GHz – 750 GHz, when (a) the shim and test port flanges have an offset in waveguide H-plane; and (b) the shim and test port have E-plane misalignment. As a reference, the measured data for perfectly mated flanges are also shown.

Figure 4.14 Comparison of measured and simulated complex reflection coefficient for the shim terminated with open-ended waveguide over the frequency range of 500 GHz – 750 GHz, when the shim and test port flanges are well-aligned. Measurement is corrected using SDD(RO) calibration with different radiating open models generated from HFSS and EMF method (as shown in Figure 4.2), respectively.

4.3.2 Delay Short Termination

Delay short is usually a preferred termination during measurements because of its well-know performance. We now examine the flange mismatch with a terminating high reflective standard – a quarter-wave delay short, in the WM-380 (500–750 GHz) frequency band. A delay short can generally be realized in two different ways: a shim backed with a flush short, or a recess milled

into a flanged short. It is found in [67] [68] that a milled delay short has smaller misalignment uncertainty than the shim type delay short. In our measurements, an SDD(RO) calibration is first performed by using a flush short, two delay shorts with nominal length 92 μm and 160 μm , and a radiating open-ended waveguide. Then a quarter-wave milled delay short is connected to the test port. Both the delay short and test port are with VDI modified UG-387 flanges, which has alignment pins of diameter 1.613 mm (tolerance +0.008/-0.000 mm) and mating holes of diameter 1.562 mm (tolerance 0.000/-0.012 mm). During measurements, the milled delay short was randomly disconnected/re-connected 6 times. Also, the flange is intentionally pushed twice in each direction to produce a maximum possible flange misalignment in waveguide E- or H-plane. A fix torque 11 cNm and four screws with tightening pattern E-W-N-S have been applied during each measurement. Two steps tightening sequence are always used during connections. In the first step, four screws are tightened provisionally (~50% of tightening torque). Next the final tightening is applied with 100% torque (11 cNm).

Figure 4.15 illustrates the measurement setup, and the corresponding circuit model and signal flow graph. The delay line has characteristic impedance Z_0 and length L . Waveguide flange misalignment between test port and delay short is represented as an equivalent shunt inductor (for H-plane offset) or shunt capacitor (for E-plane offset) with susceptance jB . It is a symmetric component, thus having $S_{11} = S_{22}$ and $S_{21} = S_{12}$. Then the reflection coefficient at test port can be found as:

$$\Gamma = \frac{b_1}{a_1} = S_{11} + \frac{(S_{21})^2 (-e^{-j2\theta})}{1 + S_{11}e^{-j2\theta}} \quad (4.19)$$

where $S_{11} = \frac{-y}{2+y}$, $S_{21} = \frac{1}{1+y/2}$, $y = \frac{jB}{Y_0} = jb$, $\theta = \beta L$. For a pair of mated flanges, misalignment is usually small, $|y| \ll 1$. Thus we have $S_{11} \approx \frac{-y}{2}$, $S_{21} \approx 1$. Equation (4.19) can then be approximated as:

$$\Gamma \approx -\frac{y}{2} - e^{-j2\theta} \quad (\text{for small waveguide offset}) \quad (4.20)$$

It shows that the magnitude of Γ at test port is close to 1, with a small correction introduced by $\frac{y}{2}$. Phase of Γ can be expressed as:

$$\angle \Gamma \approx \tan^{-1} \left(\frac{\frac{b}{2} - \sin(2\theta)}{\cos(2\theta)} \right) \quad (4.21)$$

It is close to phase of the delay short, with small correction related to the normalized admittance y of flange misalignment. The phase deviation becomes more pronounced at high frequencies for a capacitive offset, while reverse for an inductive offset.

Figure 4.16 shows corrected reflection coefficients for the quarter-wave milled delay short, and compares its theoretical performance obtained from HFSS. Six random measurements are shown in black color in each plot, while measurements done by pushing in the waveguide E- and H-planes are shown in purple and green respectively. The theoretical reflection coefficient of the delay short without flange misalignment is simulated in HFSS and the result is also included in red color. For a lossless one-port delay short circuit, the return loss is expected to be 0 dB. Return loss in Figure 4.16 (a) is close to 0 dB for random measurements, and however it is about 0.4 dB for pushed measurements. Reasons for this unexpected loss will be discussed later in

section 5.2. The dip at 557 GHz is water vapour line. Figure 4.16 (b) shows the phases of reflection coefficient for all measurements. Their slopes are similar. Measurements with random connections are in quite good agreement with simulation in HFSS using the actual delay length 147 μm . Compared with simulation, phases of measurements with E-plane waveguide offset are smaller and have more deviation at higher frequencies, while it is the opposite for measurements with H-plane offset. These agree with our analysis in equation (4.19) – (4.21). Figure 4.17 shows the calculated standard uncertainty of reflection coefficient for 6 random measurements using equation (4.16). For comparison, the standard uncertainty for uncorrected reflection coefficient data is also included. They are in good agreement as expected.

Furthermore, as an alternative method of interpreting data in Figure 4.16, we calculate the corresponding normalized admittance. The real and imaginary parts of admittances as functions of frequencies are plotted in Figure 4.18(a) and (b), respectively. Ideally, an offset in waveguide H- or E-plane is equivalent to a frequency dependent shunt susceptance at the plane of the waveguide junction. Effect from flange misalignment should appear merely in the susceptance part, and the conductance is related to the reflection from the delay short. In Figure 4.18(a), measured conductance for most random measurements is close to zero, which is as expected for a short termination. The conductance for measurements with intentional flange misalignment is within 0.05 dB, which might be caused by power leakage during connections. Note that the waterline at 557 GHz only presents in conductance plot in Figure 4.18(a), but disappears in the susceptance plot in Figure 4.18(b).

The absolute flange mismatch for this pair of VDI modified flanges can then be estimated by substituting the ideal reflection coefficient of the delay short into equation (4.19). Figure 4.19 shows the de-embedded absolute flange reflection coefficient, as well as simulation of flange

mismatch for a pair of VDI modified UG-387 flanges with the worst-case misalignment in H- and E-plane, respectively. Based on the design and machine tolerance, the maximum possible flange lateral misalignment is 0.060 mm for VDI modified UG-387 flanges, which causes as much as 8 dB return loss at WM-380 band. Our measurements are within this limit. It is also interesting that effect of E-plane misalignment shows capacitive and becomes more pronounced as frequency increases, while effect of H-plane misalignment shows inductive and becomes more pronounced as frequency decreases. These agree with theoretical study that waveguide offset in E- or H-plane is equivalent to shunt capacitance or shunt inductance at jointing plane. They are also evidence that the SDD(RO) calibration is insensitive to flange misalignment and is capable of characterizing the true reflection coefficient from flange misalignment.

(a) Experimental setup

(b) Circuit model

(c) Signal flow graph

Figure 4.15 Experimental setup and circuit model for measuring flange misalignment terminated with a delay short.

Figure 4.16 Reflection Coefficient for quarter-wave milled delay short with standard UG-387 flange in WM-380 band. (a) $|S_{11}|$ vs. frequency; (b) Phase of S_{11} vs. frequency; and (c) complex S_{11} at 625 GHz. Black data represents six times random measurements. Purple and green data show four measurements with flange misalignment along H- and E-plane, respectively. HFSS simulation using actual delay length is shown in red.

Figure 4.17 Standard uncertainty of 6 random measurements of reflection coefficient for quarter-wave milled delay short with standard UG-387 flange in WM-380 band. The uncorrected data is normalized to their average across measurements. And corrected data is calibrated using SDD(RO) method.

(a) Conductance vs. frequency

(b) Susceptance vs. frequency

Figure 4.18 (a) real and (b) imaginary parts of normalized admittance calculated from data in Figure 4.16, for quarter-wave milled delay short with flange misalignment in the WM-380 band. Black represents six random measurements. Purple and green show four measurements with H- and E-plane flange misalignment, respectively. Theoretical admittance calculated from actual delay length is shown in red.

(a) $|S_{11}|$ vs. frequency

(b) 625 GHz

Figure 4.19 Estimated absolute flange mismatch for a pair of VDI UG-387 flanges in the WM-380 band. For comparison, HFSS simulation for a pair of VDI modified UG-387 flanges with the worst-case E- and H-plane misalignment (0.060mm in each direction) is also included.

4.3.3 Waveguide Load Termination

As a third example, the SDD(RO) is applied to calibration for measurements of a flange mismatch terminated with a waveguide load. These measurements are also performed in the WM-380 frequency band. Figure 4.20 shows a photo of the measurement setup. The device under test (DUT) consists of a 25.4 mm (1") long waveguide adaptor piece and a precision waveguide load. The interface between waveguide load and adaptor piece is never disconnected during the measurements. The load is a VDI precision termination that has very low reflection (below -50 dB) at WM-380 band. Both test port and adaptor piece have experimental flange which embodies all flange designs considered in this section.

Figure 4.20 Picture of the testing setup for absolute flange mismatch measurements with waveguide load termination. DUT consists of an 1" adaptor waveguide and an 1" precision waveguide load piece. They are never disconnected during measurements.

All data are corrected using the same error coefficients of SDD(RO) calibration as those used in Section 4.2.2 for measurements of the milled delay short termination. Similarly, a fix torque 11 cNm and four screws with tightening pattern E-W-N-S have been applied during each connection. Two steps tightening sequence are used during connections. In the first step, four screws are tightened provisionally (~50% of tightening torque). Next the final tightening is applied with 100% torque (11 cNm).

During measurements, raw data are recorded for the DUT (including 1'' adaptor section and waveguide load) with six random disconnection/re-connection cycles as well as twice with pushing in each direction along the E- or H-plane at the reference plane. Similar measurements are repeated for both standard UG-387 flanges and ring-centered flanges.

Figure 4.21 shows the magnitudes of the corrected reflection coefficients for DUT with a pair of standard UG-387 flanges as well as a pair of ring-centered flanges. As expected, the repeatability of the ring-centered flange, characterized by the spread of data, is better than that of standard UG-387 flange. For the standard UG-387 flanges, it is clear that mismatch from E-plane offset is more severe than mismatch from H-plane offset. The magnitude of reflection coefficient for measurement with an intentional E-plane offset increases with frequency, while it decreases with frequency for measurement with an intentional H-plane offset. These data again agree with theoretical argument that waveguide a H- or E-plane offset is equivalent to a shunt inductance or capacitance at the jointing interface.

Figure 4.22 shows polar plots of complex reflection coefficients reduced on Smith Charts for standard UG-387 flange (shown on the left) and ring-centered flange (shown on the right). In Figure 4.22(a), reflection coefficients for all measurements are plotted for one single representative frequency at 625 GHz. In Figure 4.22(b), the complex reflection coefficients over

the entire frequency band are plotted for three sample connections, including one random measurement, one measurement when flanges are intentionally misaligned in H-plane, and one measurement when flanges have an intentional E-plane offset. The H-plane misaligned data shows inductive, while the E-plane misaligned data shows capacitive. And the E-plane flange offset results in a larger reflection than H-plane offset, as expected. The waveguide offset is expected to move $|S_{11}|$ along the $g=1$ circle on the Smith Chart. However, it appears from the data that the load conductance is not matched to the waveguide impedance. This issue will be addressed shortly in this section. The small circles in reflection coefficient data (~ -35 dB) shown in Figure 4.22 (b) indicate mismatch and standing waves. The period gives the distances between the reflection plane which is approximate 1 inch from the reference plane.

Figure 4.23 shows the real and imaginary parts of the admittance for all measurements as functions of frequency across the band. For the same device under test with different flange types, the conductance is comparable for both standard UG-387 flange and ring-centered flange. However, the susceptance for the standard UG-387 flange is about ten times larger than that for the ring-centered flanges. There is also a ~ 5 GHz period standing wave seen in plots in Figure 4.21 – Figure 4.23. This is equivalent to ~ 2 inch round trip travel in the waveguide in WM-380 band, and represents mismatch at the interfaces between the adaptor section and the load. The VDI precision waveguide load itself has very low reflection (~ -50 dB) and it is barely observable in data.

Following equation (4.16), the experimental standard deviation of the susceptance is found based on the six times random disconnection/reconnection cycles for each flange type, and results are shown in Figure 4.24. The data shows that uncertainty for the standard UG-387 flange is at least ten times worse than that for the ring-centered flange. This suggests that, for an

identical device under test, connection repeatability for the ring-centered flange is an order of magnitude better than that for the standard UG-387 flange.

(a) Standard UG-387 Flange

(b) Ring-Centered Flange

Figure 4.21 Magnitude of reflection coefficient for waveguide load termination with (a) a pair of standard UG-387 flanges, and (b) a pair of ring-centered flanges, respectively. The black lines are measurements with six times random disconnection/reconnection at the reference plane. Purple and green colors show four times with intentionally pushing toward waveguide H- and E-plane, respectively.

(a) Complex S_{11} at 625 GHz. (b) Complex S_{11} over entire frequency band for three sample measurements.

Figure 4.22 Complex reflection coefficients for waveguide load termination in the WM-380 band with, Left: a pair of standard UG-387 flanges; and Right: a pair of ring-centered flanges. Plots in (a) show complex S_{11} at 625 GHz. Plots in (b) show complex S_{11} over entire frequency band for three sample measurements. Black represents random measurement. Purple and green colors represent measurements with intentionally H- and E-plane waveguide misalignment, respectively. Note the different scales between left plots and right plots.

Figure 4.23 Real and imaginary parts of normalized admittance as functions of frequency from data in Figure 4.17, for (a) Standard UG-387 flange, and (b) Ring-centered flange. Note the different scales for the susceptance plots.

Figure 4.24 Experimental standard deviation of susceptance from Figure 4.19 for the standard UG-387 flange and the ring-centered flange. Calculation is based on the 6 random measurements for each flange.

From Figure 4.22, the load reflection coefficient does not lie on the $g = 1$ circle, but has a measured return loss of ~ 23 dB. This is unexpected and surprising. Ideally, a flange misalignment produces a shunt susceptance, and this only moves data along constant conductance circles. Thus, the reflection coefficient data is expected across the center on the Smith Charts in Figure 4.22. Also the conductance in Figure 4.23 is expected to be close to unity.

To explain this discrepancy, several studies were performed. Initially, it was assumed that calibration error resulting from limited modeling precision of radiating open-ended waveguide standard would explain this. We estimated the reflection coefficient of the open-ended

waveguide from HFSS calculations assuming a flat infinite half plane. However, HFSS is a general-purpose three-dimensional simulator and employs complicated meshing strategies and solution algorithms. As a result, the accuracy of HFSS calculations depends on a number of specific details of the analysis. Furthermore in practice, pins, the raised boss and other flange artifacts (as well as the finite dimension of the flange) could impact the reflection coefficient of a radiating open-ended waveguide, and we do not consider these effects in our simulation. To address this issue, the sensitivity of SDD(RO) calibration was investigated by applying different error networks produced by different models for the radiating open standard, including various simulations in HFSS by considering different sizes of radiating boxes, and also the simple model using EMF analysis. However, the ~ 23 dB offset of reflection coefficient on the Smith Chart is still observed when applying different models for the radiating open standard in SDD(RO) calibration. It suggests that radiating open model is not responsible for the unexpected offset in data.

Alternatively, the offset was postulated as due to a change in characteristic impedance because of possible waveguide dimension tolerances. Approximate analytical formulas for the reflection coefficients of junctions of waveguides with slightly different dimensions are given by Banister et al. [69], and electromagnetic simulations are presented in [22]. Similarly we employed HFSS to the effect of a mated pair of rectangular waveguides whose a - and b -dimensions include small differences based on known tolerances in the WM-380 frequency band. Assuming both a - and b -dimension is specified with the same tolerance, $\pm t$. As shown in Figure 4.25, one waveguide has the maximum possible width ($a + t$) and minimum possible height ($b - t$), while the other has minimum width ($a - t$) and maximum height ($b + t$). In Figure 4.26, one waveguide has the maximum possible width ($a + t$) and height ($b + t$), but the other has

minimum width ($a - t$) and height ($b - t$). It is clear that the mismatch due to changing in impedances occurs when there is a small dimension difference between the pair of mated waveguides. This also suggests that the configuration in Figure 4.26 produces a relatively larger reflection than that in Figure 4.25. It is interesting and surprising that a change in waveguide nominal width of only 2% can result in a return loss as much as 22 dB, which is close to that observed in the data of Figure 4.22.

Figure 4.25 Simulated complex reflection coefficient for a junction of two rectangular waveguides of dimensions $(a - t) \times (b + t)$, and $(a + t) \times (b - t)$, respectively. Note in the legend, tolerance t is shown with unit of waveguide nominal dimension a . Simulation is done in the WM-380 frequency band.

Figure 4.26 Simulated complex reflection coefficient for a junction of two rectangular waveguides of dimensions $(a + t) \times (b + t)$, and $(a - t) \times (b - t)$, respectively. Note in the legend, tolerance t is with unit of waveuide normal dimension a . Simulation is done in the WM-380 frequency band.

To further verify these findings, we carefully measured the actual dimensions of the waveguide pieces used in the measurements with a three-dimensional white-light interferometer from Veeco [70]. As shown in Figure 4.27, one of the waveguides has dimensions $0.391 \text{ mm} \times 0.193 \text{ mm}$, while the other has dimensions $0.381 \text{ mm} \times 0.203 \text{ mm}$.

Applying these actual waveguide dimensions and terminating with a perfect match, a simulation in HFSS is run and results are shown in Figure 4.28. Various waveguide offset in H-plane or E-plane are also included in simulation. It shows clearly that the simulation data, without any waveguide misalignment, is not at the center of Smith Chart. This also suggests that the mode impedance of the waveguide is different than its nominal value due to differences in the waveguide's dimensions. This effect is more pronounced at lower frequencies.

Figure 4.29 compares simulation using actual waveguide dimensions with earlier measurements from Figure 4.22(b) for a pair of standard UG-387 flanges terminated with waveguide load. It shows that the simulation (red) and measurement (navy) without waveguide offset are similar and both shifted from the center of Smith Chart. Simulation of this pair of waveguides including $(0.24*a)$ offset in H-plane or $(0.28*a)$ offset in E-plane is also presented, where a is the nominal waveguide width (0.381 mm in the WM-380 band). They are similar to measurements when pushing to cause a maximum possible flange misalignment in the H- or E-plane.

A Monte Carlo simulation of the reflection coefficient for this pair of waveguides, of dimensions $(0.391 \text{ mm} \times 0.193 \text{ mm})$ and $(0.381 \text{ mm} \times 0.203 \text{ mm})$, was also performed with uniform distributed H- or E-plane misalignments within limits $\pm (0.24*a)$ and $\pm (0.28*a)$, respectively, and terminated with a perfect match. Figure 4.30 shows the simulation results at 625 GHz , and compares them with measurements in Figure 4.22(a) for a pair of standard UG-

387 flanges terminated with waveguide load. Agreement between simulation and measurement is close.

While the waveguide dimension difference explains the change of characteristic impedance, the flange misalignment at the reference plane is responsible for the variation of susceptance in measurements. Assuming the equivalent susceptance caused by flange misalignment B_{flange} is equal to the measured susceptance at the test port B_m :

$$Y_{flange} = jB_{flange} = jB_m$$

The actual reflection coefficient for a pair of flanges can then be estimated from measured susceptance in Figure 4.23, following:

$$\Gamma_{flange} = \frac{Y_0 - (Y_0 + jB_m)}{Y_0 + (Y_0 + jB_m)} = \frac{-jB_m}{2Y_0 + jB_m}$$

where Y_0 is the admittance for TE₁₀ mode.

Figure 4.31 shows the magnitudes of estimated flange absolute mismatch for a pair of standard UG-387 flanges as well as a pair of ring-centered flanges. Figure 4.32 shows their complex reflection coefficients at an example frequency 625 GHz. Magnitude of reflection coefficient for measurements with intentional H-plane offset decreases with frequency, while those with E-plane offset increases with frequency. H-plane misaligned data shows inductive and E-plane misaligned data shows capacitive. These again agree with theoretical analysis that H- and E-plane waveguide offset is equivalent to shunt conductance and shunt capacitance, respectively. The worst-case return loss for standard UG-387 flange is worse than 5 dB, and for the ring-centered flange is about 25 dB for most of the band.

Figure 4.33 simulates reflection coefficient caused by the worst-case H- and E-plane misalignment for a pair of standard UG-387 flanges and a pair of ring-centered flanges in the WM-380 band. For the standard UG-387 flange, alignment is made by outer pins and holes. The diameter for the pins is defined as 1.562 mm (tolerance +0.000/-0.013 mm) with position tolerance 0.076 mm. The diameter of the mating holes is 1.702 mm (tolerance +0.025/-0.000 mm), with position tolerance 0.051 mm. Thus the maximum possible waveguide misalignment in H- or E-plane is 0.152 mm for a pair of standard UG-387 flanges. For ring-centered flange, the lateral alignment is done between boss and ring. The diameter of boss is 9.525 mm (tolerance +0.000/-0.005 mm) with position tolerance 0.005 mm. Diameter of the ring is 9.528 mm (tolerance +0.003/-0.000 mm). Thus the maximum H- or E-plane waveguide misalignment between a pair of ring-centered flanges is 0.015 mm. Simulation shows that effect of E-plane misalignment is more severe than that of H-plane misalignment for both flange types. The simulated worst-case return loss is close to 0 dB for standard UG-387 flanges, and about – 28 dB for the ring-centered flange. These are comparable with our measurements in Figure 4.31.

The resulting standard deviation based on the six random measurements is calculated base on equation (4.16) and is plotted in Figure 4.33 for three different types of flanges. Data for standard UG-387 flange and ring-centered flange is based on measurements from Figure 4.31, while data for VDI modified UG-387 flanges is based on data from Figure 4.19. As expected, the ring-centered flange shows the best connection repeatability, and the standard UG-387 flange shows the worst.

X	0.80	-	-	mm
Y	0.44	-	-	mm
Ht	-	-	-	um
Dist	-	-	-	mm
Angle	-	-	-	°

Title:

X	0.53	-	-	mm
Y	0.50	-	-	mm
Ht	-	-	-	um
Dist	-	-	-	mm
Angle	-	-	-	°

Title:

Figure 4.27 Actual waveguide dimensions of WM-380 pieces used in experiments, measured by using a three-dimensional white-light interferometer from Veeco. It shows one waveguide has dimensions $0.391 \text{ mm} \times 0.193 \text{ mm}$, while the other has dimensions $0.381 \text{ mm} \times 0.203 \text{ mm}$.

(a) With H-plane waveguide offsets

(b) With E-plane waveguide offsets

Figure 4.28 Simulation of reflection coefficient for a pair of waveguides of dimensions $0.391 \text{ mm} \times 0.193 \text{ mm}$, and $0.381 \text{ mm} \times 0.203 \text{ mm}$ in the WM-380 band. Various waveguide offsets (a) in H-plane and (b) in E-plane are included. The offset values in the legend are shown in unit of waveguide width 0.381 mm .

Figure 4.29 HFSS simulation and measurements of reflection coefficient for a pair of mated rectangular waveguides with unequal dimensions, and terminated with a perfect match in the WM-380 band. One waveguide has dimensions $(0.391 \text{ mm} \times 0.193 \text{ mm})$ and the other has dimensions $(0.381 \text{ mm} \times 0.203 \text{ mm})$. Measurements are from Figure 4.22(b) for a pair of standard UG-387 flanges terminated with waveguide load.

Figure 4.30 Monte Carlo simulation of reflection coefficients for a pair of waveguides of unequal dimensions, $(0.391 \text{ mm} \times 0.193 \text{ mm})$ and $(0.381 \text{ mm} \times 0.203 \text{ mm})$ respectively, and terminated with a perfect match in the WM-380 band. Waveguide offsets in H- and E-plane are of uniform distribution within limits $\pm (0.24 \cdot a)$ and $\pm (0.28 \cdot a)$, respectively, where a is the nominal waveguide width 0.381 mm . Results are only shown for an example frequency 625 GHz , but the rest frequencies resemble. For comparison, measurements from Figure 4.22(a) for a pair of standard UG-387 flanges terminated with waveguide load are also included.

(a) Standard UG-387 flange

(b) Ring-centered flange

Figure 4.31 Estimated absolute flange mismatch in the WM-380 band for (a) a pair of standard UG-387 flanges, and (b) a pair of ring-centered flanges. Results for six times random disconnection/reconnection cycles are shown in black, while results for measurements with intentional H- or E-plane flange misalignment are shown in purple and green, respectively.

Figure 4.32 Estimated absolute flange mismatch in the WM-380 band shown on Smith Charts for (a) a pair of standard UG-387 flanges, and (b) a pair of ring-centered flanges. Results are shown at example frequency 625 GHz. Note the different scales between two plots.

(a) Standard UG-387 flange

(b) Ring-centered flange

Figure 4.33 HFSS simulation of the worst-case reflection coefficient for (a) a pair of standard UG-387 flanges, and (b) a pair of ring-centered flanges, in the WM-380 band. The maximum possible lateral misalignment for standard UG-387 flange is 0.152 mm, and it is 0.015 mm for the ring-centered flange.

Figure 4.34 The experimental standard deviation of flange absolute S_{11} based on the six random measurements for a pair of standard UG-387 flanges, a pair of ring-centered flanges, and a pair of VDI modified UG-387 flanges, respectively.

4.4 Conclusions

A calibration technique insensitive to flange misalignment has been analyzed and applied to characterize reflection coefficient for a pair of misaligned waveguide flanges. Performance of the calibration method has been verified in the WM-380 band. Results demonstrated its high precision as well as relatively smaller uncertainty compared with connection repeatability for various flange types.

Using this calibration method, reflection coefficient for a pair of mated flanges connected to three different terminations, including a radiating waveguide shim, a milled quarter-wave delay short, and a precision waveguide load, has been measured. With the radiating shim termination, the measured return loss has been correlated with the physical offset of the waveguide, and results have shown good agreement between measurements and analytical formulas by Harrington. Using a high-reflected delay short termination and a near-matched waveguide load termination, absolute reflection coefficient for a pair of VDI modified UG-387 flanges, a pair of standard UG-387 flanges, and a pair of ring-centered flanges has been characterized. Results are in good agreement with theory that a small waveguide misalignment in H- or E-plane is equivalent to a shunt inductance or a shunt capacitance at the plane of the waveguide junction. Results also show the connection repeatability for ring-centered flange is superior to that for VDI modified UG-387 flange and standard UG-387 flange.

However, it should be noted that the SDD(RO) calibration method also has limitations. As shown in Figure 4.3 and Figure 4.9, model of radiating open standard and loss in delay short standard both can introduce error in reflection coefficient measurements below ~ -30 dB. In order to have higher precision, a more precise model of radiating open, including effect of flange boss, pins, and dimension, should be used. Loss of delay short standards due to waveguide and junction should also be considered.

Figure 4.35 compares reflection coefficient of a shim terminated with radiating open corrected using different one-port calibration methods, including SDD(RO), SDD, and SDL. HFSS simulation and measurement of the radiating shim is from Figure 4.14 when the shim and test port are well aligned. Phases of delay short standards in SDD and SDL calibrations are found using SDD(RO) calibration. The load standard in SDL is a high precision waveguide load with

ring-centered flange. It shows that the SDL calibration is most accurate provided that the phase of the delay short standard is known accurately and the load is well-matched with minimal flange offset.

Figure 4.35 Reflection coefficient of radiating shim without flange misalignment in the WM-380 band, corrected using different one-port calibration methods, including SDD(RO), SDD, and SDL. Simulation and measurement raw data are from Figure 4.14. For SDD calibration, phases of two delays standards are found using SDD(RO). For SDL calibration, exact phase of delay short is also found using SDD(RO) method, while the load standard is a WM-380 precision load with ring-centered flange.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

To keep pace with the emerging applications in submillimeter-wave region, this work has addressed a major limitation of precision measurements for rectangular waveguide systems. A new design of waveguide flange has been presented to be applied at millimeter and submillimeter frequencies, and several measurement metrologies associated with precisely characterizing performance of flanges have been investigated. Modifications of the ring-centered flanges have been suggested for better compatibility with all existing designs and capability of performing traditional two-port TRL or LRL VNA calibrations. The superior alignment, full backward compatibility, and simple design make the ring-centered flange one of the most robust candidates being considered by IEEE P1785 group as a new international standard for waveguide interfaces for use above 110 GHz.

In order to evaluate performance of flanges at submillimeter-wave frequencies, several different techniques have been discussed and compared. Measurements using each of these

methods confirm excellent connection repeatability of the ring-centered flange over the standard UG-387 flange and its modified versions. VNA time-gating technique was initially applied as it provides both flange absolute mismatch and connection repeatability information at the same time. However, selection of gate width must be no narrower than the VNA system response resolution in the time domain, which depends on the frequency span of measurements as well as the window function applied in the frequency-to-time and time-to-frequency transforms. As the specific implementation and normalization differs between VNA manufacturers, the time-gating technique introduces complexity in interpreting data and care needs to be taken when measuring small reflections from a pair of mated waveguide flanges. In favor of simplicity and directness, a load-separation technique was applied for characterizing connection repeatability for various candidate flanges currently under consideration by IEEE P1785 group and standard UG-387 flanges in several millimeter and submillimeter frequency bands. This method defines the initial measurement as a match standard and all subsequent disconnection/reconnection measurements are referred to this measurement. By selecting the average on all connections as the match standard and using a vertical VNA system to overcome gravity bias, the load-separation method provides useful measurements for flange repeatability. Although it does not providing flange absolute mismatch information, the load-separation is a user preferred method for examining flange connection repeatability for its simplicity and intuition.

Finally, the true flange mismatch can be characterized by using a calibration scheme that is insensitive to flange misalignment. Performance of the calibration method has been verified in the WM-380 frequency band. Results show that it has within $\pm 3^\circ$ (-26 dB) precision across the full band, and has relatively small uncertainty compared with the connection repeatability for flanges. Better precision of SDD(RO) calibration can be achieved using more precise model of

radiating open and considering loss of delay short standards. Using SDD(RO) calibration method, the reflection coefficient for a pair of mated flanges connected to three different terminations, including a radiating waveguide shim, a milled quarter-wave delay short, and a waveguide load, has been studied. Measurements show good agreement with theory that a small waveguide misalignment in H- or E-plane is equivalent to a shunt inductance or a shunt capacitance at the plane of the waveguide junction. The absolute reflection coefficient for standard UG-387 flange, VDI modified UG-387 flange, and ring-centered flange agrees with their simulation and the ring-centered flange is an order of magnitude more repeatable than the standard UG-387 flange.

5.2 Future Work

This work is fundamental and of a practical nature. Applications of the ring-centered flange and measurement metrologies are generally broad. They are useful in any rectangular waveguide system that requires high precision measurements, especially in the submillimeter-wave frequency region.

In the future, the flange absolute mismatch measurement metrology discussed in Chapter 4 should be applied to all the candidate designs which are currently being considered by IEEE P1785 study group for evaluation as possible standards for waveguide interfaces as listed in Chapter 2. These measurements will be valuable for the entire metrology community to understand each design more comprehensively and to make better design choices and decisions on choosing new flange standard.

In addition to flange misalignment, other issues from this work are also found to degrade waveguide connections. It was noticed in the measurements presented in Chapter 4 that waveguide dimension tolerances can be significant enough to cause a change in mode impedance. This effect becomes as significant as flange misalignment at submillimeter frequencies, and it illustrates a potential need for better waveguide machine technologies.

It was also found that flange mating methods have a profound effect on connection uncertainty and precision. Four screws are conventionally employed for flange connection. However, the screw torque recommended from organizations differs over a large range [24] [71]. For the standard UG-387 flanges with MIL specified #4-40 captive stainless steel screws, the optimal torque suggested by Flan Microwave Ltd. is about 6 cNm, 11cNm from NIST, 44 cNm from ALMA, and 51 cNm from several other organizations (Cobham Continental Microwave, Space Machine & Engineering Corp, and Teledyne MEC, etc.). A few groups, including UVA, NIST, Agilent, and NAOJ at Japan, have even started using paper clips or clamps instead of screws for flange connections.

Initial measurements on uncertainty of reflection coefficient associated with three different screw torques are illustrated in Figure 5.1. Tests performed with the load-separation technique described in Chapter 3 show that the measurement uncertainty is the lowest for 11 cNm, and then followed by 44 cNm and 51 cNm.

Figure 5.2 shows reflection coefficient of a milled delay short corrected using SDD(RO) method. Similar to measurements in Figure 4.16 but a tighter screw torque 44 cNm is used. Standard uncertainty for 6 random measurements is plotted in Figure 5.3. It shows that measurements with 44 cNm torque have smaller loss at the junction, while data taken with 11

cNm has better repeatability. Much work is still needed to be done on this issue to better understand the problem and find the best method for mating flanges at submillimeter waves.

Figure 5.1 Measurement uncertainty of reflection coefficient associated with different screw torques in the WM-380 frequency band. With the load-separation technique, six times random disconnection/reconnection cycles are recorded for the same pair of waveguide flanges with screw torques 51 cNm, 44 cNm, and 11 cNm, respectively.

(a) Magnitude of reflection coefficient

(b) Phase of reflection coefficient

Figure 5.2 Reflection coefficient measured using 44 cNm screw torque for a quarter-wave milled delay short with standard UG-387 flange in WM-380 band. Measurements are similar to those shown in Figure 4.16, but used a tighter screw torque. (a) $|S_{11}|$ vs. frequency; (b) Phase of S_{11} vs. frequency. Black data represents six times random measurements. Purple and green data show four measurements with flange misalignment along H- and E-plane, respectively. HFSS simulation using actual delay length is shown in red.

Figure 5.3 Standard uncertainty of 6 random measurements of reflection coefficient for quarter-wave milled delay short in the WM-380 band. Similar measurements are taken with different screw torques, 11 cNm and 44 cNm. Data is from Figure 4.16 and Figure 5.2.

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