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Evaluating the Effect of Using Precision Alignment Dowels on Connection Repeatability of Waveguide Devices at Frequencies from 750 GHz to 1.1 THz

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Abstract—This paper describes an investigation into the effects of using additional precision alignment dowel pins on the connection repeatability performance of waveguide interfaces at submillimeter-wave frequencies. The waveguide interface type that was used for this investigation is an adapted version of the 'precision' UG-387 (i.e. based on the MIL-DTL-3922/67 design), manufactured by Virginia Diodes, Inc. The investigation was undertaken in the WM-250 waveguide band (i.e. at frequencies ranging from 750 GHz to 1.1 THz). Connection performance is compared with and without the use of added precision dowel pins in the inner dowel holes of this flange type. The repeatability of the measurements is assessed using statistical techniques, in terms of the experimental standard deviation in both the real and imaginary components of the complex-valued linear reflection coefficient.

Index Terms—Measurement repeatability, Submillimeter-wave measurements, VNA measurements, Waveguide flanges, Waveguide interfaces, Waveguide measurements

1. INTRODUCTION

Two recent papers [1, 2] have presented investigations into the connection repeatability of some waveguide devices operating from 750 GHz to 1.1 THz (i.e. in the WM-250 waveguide size [3]). In both these earlier investigations, the waveguide flanges were aligned during connection using four alignment dowel holes and dowel pins situated on the front faces of the flanges. These alignment dowel pins are permanently fitted to the flanges. During the connection of two waveguide flanges, two dowel pins on one of the flanges fit into two dowel holes on the other waveguide flange, and vice versa.

This connection strategy follows the so-called UG-387 flange design (described in [4] and earlier editions, e.g. [5, 6], etc), which has been in existence for many years. However, the performance of this flange design has long been known to be poor at high millimeter-wave and submillimeter-wave frequencies, where the relatively loose tolerances on the specified diameters of the dowel pins and dowel holes cause performance degradation in the electrical measurements (i.e. significant mismatch and lack of connection repeatability). This has led to various improvements being made to this original design by different manufacturers. These improvements can broadly be described as being of two types: (i) the use of tighter tolerances on the above-mentioned outer alignment dowel holes and dowel pins; and/or (ii) the inclusion of two additional inner alignment dowel holes situated immediately above and below the waveguide aperture. These inner alignment dowel holes allow additional dowel pins to be inserted into both flange faces during connection.

Fig. 1 shows a photograph of a flange that features both the outer dowel pins and dowel holes (used for the traditional UG-387 connection strategy) and the additional inner alignment dowel holes (to which additional dowel pins are inserted during connection). The other holes shown in this Figure (situated at north, south, east and west positions around the flange face) are threaded holes to enable screws to be used to tighten the connection between two flange faces.

The flanges used in the earlier investigations [1, 2] feature both above-mentioned alignment improvements. However, only the outer dowel pins and dowel holes were used for aligning the flanges during these earlier investigations.

The purpose of the work described in this paper is to investigate the effect on flange connection repeatability of using dowel pins in the two inner alignment dowel holes. This work used the same VNA test port and devices under test (DUTs) that were used for the previous investigations [1, 2]. This enabled comparisons of connection repeatability performance to be made directly with these earlier investigations.

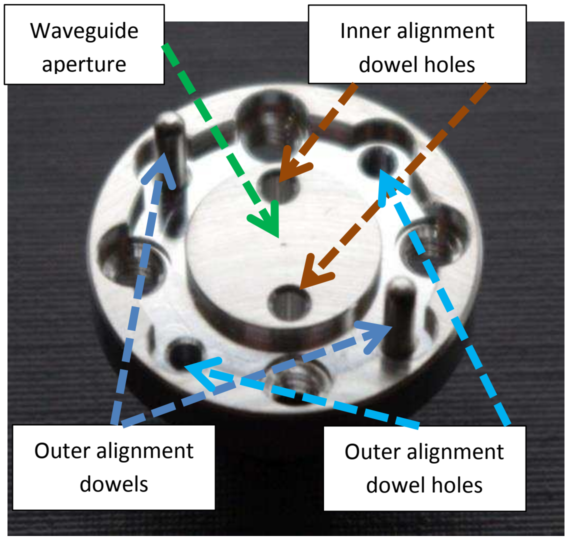

Fig. 1. Waveguide flange showing the outer alignment dowel pins and dowel holes, and, the inner alignment dowel holes. The WM-250 rectangular *waveguide aperture is 250 μm × 125 μm* – barely visible to the naked eye

The investigation described in this paper used the inner alignment dowel holes in conjunction with two different types of dowel pin:

(i) Typical dowel pins for use with these dowel holes, found in some manufacturers' calibrations kits;

(ii) Dowel pins that emulate a connection strategy that is being developed in a new IEEE standard [7]. This connection strategy uses dowel pins with different nominal diamaters.

This paper compares the connection repeatability performance achieved using both the above types of dowel pins, and also compares the achieved performance with the connection repeatability performance reported previously in [2]. Flange connection performance is assessed by calculating the experimental standard deviation of a series of repeated flange connections. Results are presented as graphs showing experimental standard deviation versus frequency.

2. METHOD

2.1 Experimental set-up

The VNA system used for the investigation comprised an Agilent Technologies PNA-X VNA connected to WM-250 (WR-01) waveguide extender heads, manufactured by Virginia Diodes, Inc (VDI). This is the same system and set-up that was used for the previous repeatability investigations [1, 2]. Following the procedure adopted in [2], the extender head was arranged so that the waveguide test port pointed vertically upwards. This arrangement minimizes any effect due to gravity on the alignment of the waveguide flanges. As with the previous investigations [1, 2], the power used to measure each Device Under Test (DUT) was around −35 dBm (0.3 μW) and the VNA's IF bandwidth was set to 30 Hz with no numerical averaging. The VNA system and set-up, shown in Fig. 2, is situated in the Roger Pollard High Frequency Measurements Laboratory (this being a temperature-controlled laboratory) at the School of Electronic and Electrical Engineering, University of Leeds, UK.

The VNA system was calibrated using a one-port 'three-known-loads' calibration technique. The 'known loads' (i.e. calibration standards) were an offset short-circuit, a 'flush' short-circuit and 'near-matched' load (from a VNA calibration kit supplied by VDI). The offset short-circuit and near-matched load were used subsequently as the DUTs for the repeatability investigation. It was not possible to use the flush short-circuit as a DUT for this investigation because the flange did not include the two inner alignment dowel holes. The offset short-circuit and near-matched load were the same DUTs that were used in [1, 2].

The connection repeatability procedure followed that given in [2], where the repeatability exercise includes connections of the DUTs where the orientation of the flange is inverted before being reconnected to the VNA test port. By inverting the waveguide flange, the imperfect position of the alignment dowel pins and dowel holes will, in principle, cause a systematic change in the VNA's electrical measurements. This systematic change will be present in the repeatability data sets along with the random changes cause by the tolerances on the diameters of the alignment dowel pins and dowel holes.

For each flange connection orientation (i.e. either inverted or non-inverted), the complex-valued linear reflection coefficient of each DUT was measured 12 times, disconnecting and re-connecting the DUT between each re-measurement. This produced a set of 12 separate determinations of reflection coefficient for each DUT in each of the two orientations. Therefore, a total of 24 dis-connect / reconnect measurements were made for each of the two DUTs. All measurements were made from 750 GHz to 1.1 THz at regular intervals of 1.75 GHz across the band.

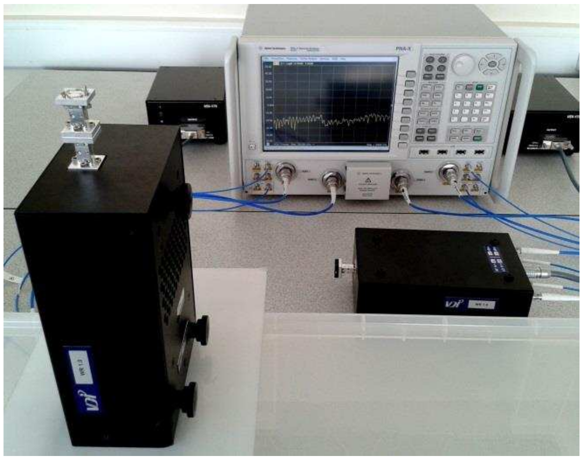

Fig. 2. The 750 GHz to 1.1 THz VNA system used for the measurements

2.2 Flange connection methods

(a) Same-diameter inner dowel pins: This flange connection method used two additional dowel pins inserted into the flanges' inner alignment dowel holes. The two dowel pins used for this connection method were of the same nominal diameter. The purpose of this flange connection method is to emulate the conventional use of these inner alignment dowel holes. Some manufacturers supply these types of dowel pin in VNA calibration kits and so two such dowel pins (in this case, from a calibration kit manufactured by Flann Microwave Ltd) were used for this purpose.

A measurement of the diameter of both of these dowel pins, made using a digital micrometer, showed the diameter of one pin to be 1.555 mm and the other pin to be 1.556 mm.

(b) Different-diameter inner dowel pins: This flange connection method also used two additional dowel pins inserted into the flanges' inner alignment dowel holes. However, for this connection method, each dowel pin was chosen to have a different diameter. This is to emulate the connection strategy being proposed for a flange design in a draft IEEE standard [7] that is currently under development. This strategy uses two dowel pins with different diameters. The dowel pin with the larger diameter achieves a very close fit to the flanges' dowel holes and provides planar alignment for the waveguide apertures. This is called the "Planar Alignment Dowel" pin. The dowel pin with the smaller diameter achieves a looser fit to the flanges' dowel holes and provides angular alignment for the waveguide apertures. This is called the "Angular Alignment Dowel" pin.

The IEEE flange design uses inner dowel holes of a specific diameter, and associated dowel pins to fit these holes accordingly. The nominal diameter of the IEEE flange inner dowel holes is 1.570 mm. The nominal diameter of the IEEE flange Planar Alignment Dowel pin is 1.566 5 mm and the nominal diameter of the Angular Alignment Dowel pin is 1.556 mm.

The engineering drawing for the flange type used for the VNA test ports and DUTs (both manufactured by VDI), used in this exercise, is shown in Fig. 3. This Figure shows that the nominal diameter of the inner alignment dowel holes is 0.0625 inches (i.e. 1.588 mm) – i.e. this is not the same diameter that is proposed in the draft IEEE standard [7]. So it is not possible to follow exactly the connection strategy advocated by the IEEE standard for this particular flange design.

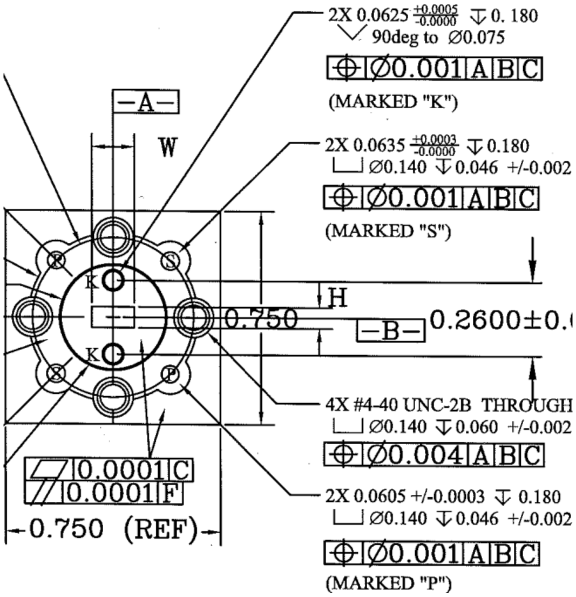

Fig. 3. Engineering drawing extract of the flange used for this investigation. The inner dowel hole diameter value (0.0625″) is shown in the top right-hand corner of the drawing

However, the connection strategy can be emulated by selecting dowel pins that, as far as possible, perform a similar role to the planar and angular alignment dowel pins used with the IEEE flange design. In order to do this, a series of dowel pins of various diameters, ranging from 1.550 mm to 1.625 mm in 0.005 mm step sizes, was obtained. These dowel pins were inserted into the flanges' dowel holes – starting with the smallest diameter dowel pin and using increasingly larger diameter dowel pins until a diameter size was found that provided the closest fit to the dowel hole size. This dowel was then considered to perform a role similar to the Planar Alignment Dowel pin used for the connection strategy described in the draft IEEE standard [7]. A measurement, made using a digital micrometer, of the diameter of the selected dowel pin showed the diameter to be 1.586 mm. (The nominal diameter for the selected dowel pin was 1.590 mm, i.e. showing the measured value to be within 4 µm of the nominal value.)

A second dowel pin was then selected with a nominal diameter of 10 µm less than the Planar Alignment Dowel (i.e. with a nominal diameter of 1.580 mm). This 10 µm difference in the pin diameters is similar to the difference in diameter between the Planar and Angular Alignment Dowels used in the draft IEEE standard (i.e. 10.5 µm). Therefore, the 1.580 mm diameter dowel pin was considered to perform a similar role as the Angular Alignment Dowel pin in the draft IEEE standard [7]. A measurement of the diameter of this dowel pin, made using a digital micrometer, showed the diameter to be 1.576 mm (i.e. within 4 µm of the nominal value).

(c) No inner dowel pins: The repeatability exercise reported in [2] did not use the flange inner alignment holes for aligning the flanges during connection. Instead, only the outer alignment dowel pins and holes were used during that exercise. However, this earlier exercise used the same test port flanges and the same DUTs as used during this current investigation. Therefore, the results obtained in the earlier exercise [2] can be used to provide equivalent repeatability data for these flanges when used without the aid of the inner alignment dowel pins and holes.

2.3 Data Analysis

The analysis uses calculations of the experimental standard deviation (as used previously in [1, 2]) as the measure of variability in the observed values due to flange connection repeatability. This computation is applied separately to both the real and imaginary components of the complex-valued linear reflection coefficient. An analysis based on using the magnitude and phase components of the reflection coefficient is avoided due to problems with such calculations that have been described in [8].

Let Γ be the complex-valued linear reflection coefficient written in terms of its real, Γ_R, and imaginary, Γ_I, components as follows (with $j^2 = -1$):

$$\Gamma = \Gamma_R + j\,\Gamma_I \tag{1}$$

For n repeated determinations of Γ, the arithmetic mean of Γ_R is given by:

$$\overline{\Gamma}_R = \frac{1}{n}\sum_{i=1}^{n} \Gamma_{R_i} \tag{2}$$

and the experimental variance is given by:

$$s^2\left(\Gamma_{R_i}\right) = \frac{1}{n-1}\sum_{k=1}^{n}(\Gamma_{R_k} - \overline{\Gamma}_R)^2 \tag{3}$$

The experimental standard deviation, $s(\Gamma_{R_i})$, is equal to the positive square root of $s^2(\Gamma_{R_i})$.

Similarly, the arithmetic mean of Γ_I is given by:

$$\overline{\Gamma}_I = \frac{1}{n}\sum_{i=1}^{n} \Gamma_{I_i} \tag{4}$$

and the experimental variance is given by:

$$s^2\left(\Gamma_{I_i}\right) = \frac{1}{n-1}\sum_{j=1}^{n}(\Gamma_{I_j} - \overline{\Gamma}_I)^2 \tag{5}$$

The experimental standard deviation, $s(\Gamma_{I_i})$, is equal to the positive square root of $s^2(\Gamma_{I_i})$.

For each DUT at each frequency, values of $s(\Gamma_{R_i})$ and $s(\Gamma_{I_i})$ are calculated for the following three situations:

(i) Using the 12 repeat measurements of the flange when connected in the non-inverted orientation. Following the convention used in [2], we use a superscript N to indicate this 'Non-inverted' situation – i.e. Γ_R^N for the real component, and Γ_I^N for the imaginary component;

(ii) Using the 12 repeat measurements of the flange when connected in the inverted orientation. Following the convention in [2], we use a superscript I to indicate this 'Inverted' situation – i.e. Γ_R^I for the real component, and Γ_I^I for the imaginary component;

(iii) Using all 24 repeated measurements of the flange connected in both inverted and non-inverted orientations. Following the convention in [2], we use a superscript IN to indicate this 'Inverted and Non-inverted' situation – i.e. Γ_R^{IN} for the real component, and Γ_I^{IN} for the imaginary component.

3. RESULTS

For each of the three flange connection methods, for both the offset short-circuit and the near-matched load, we can compare calculated values of the experimental standard deviations in the real component, $s(\Gamma_{R_i}^{N})$, $s(\Gamma_{R_i}^{I})$ and $s(\Gamma_{R_i}^{IN})$, and, we can compare the calculated values of the experimental standard deviations for the imaginary component $s(\Gamma_{I_i}^{N})$, $s(\Gamma_{I_i}^{I})$ and $s(\Gamma_{I_i}^{IN})$.

This is shown in Figs. 4 to 15, where the labels 'Same-diameter pins', 'Different-diameter pins' and 'No pins' are used to identify the three flange connections methods described in sub-section 2.2, i.e. (a) 'same-diameter inner dowel pins', (b) 'different-diameter inner dowel pins' and (c) 'no inner dowel pins', respectively.

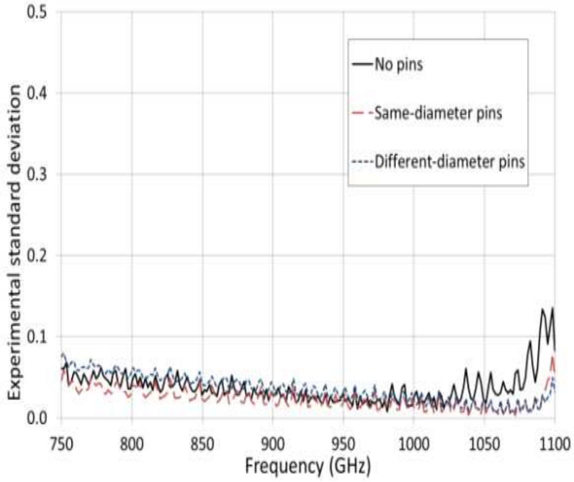

Fig. 4. $s(\Gamma_{R_i}^{N})$ for the offset short-circuit

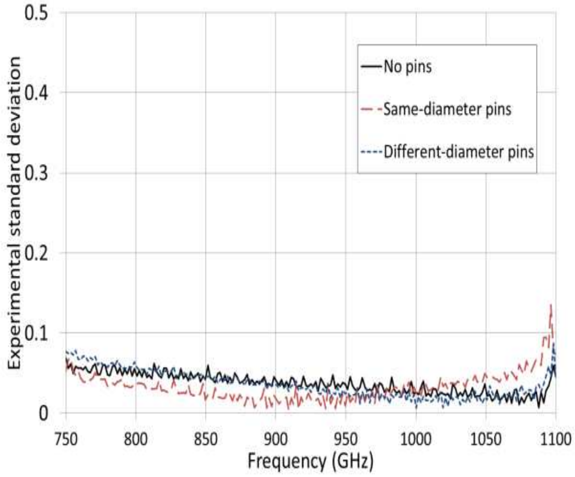

Fig. 5. $s(\Gamma_{R_i}^{I})$ for the offset short-circuit

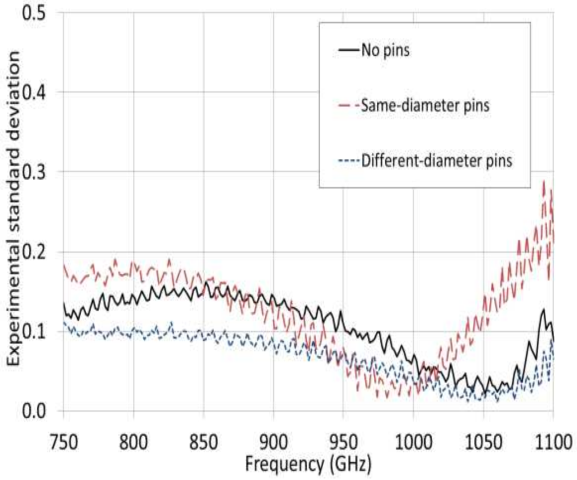

Fig. 6. $s(\Gamma_{R_i}^{IN})$ for the offset short-circuit

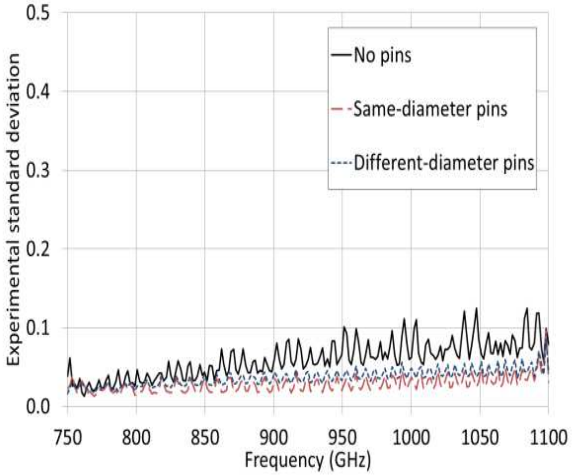

Fig. 7. $s(\Gamma_{I_i}^{N})$ for the offset short-circuit

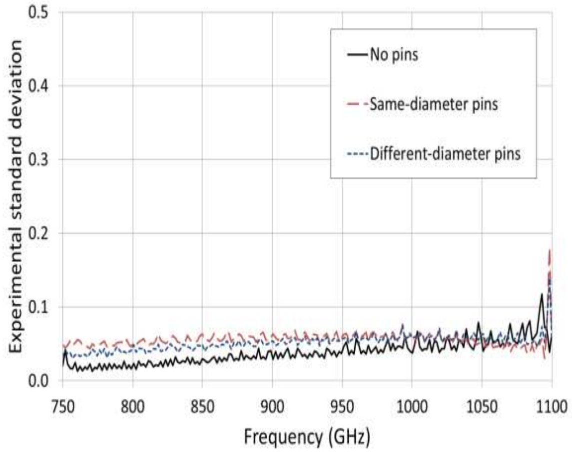

Fig. 8. $s(\Gamma_{I_i}^{I})$ for the offset short-circuit

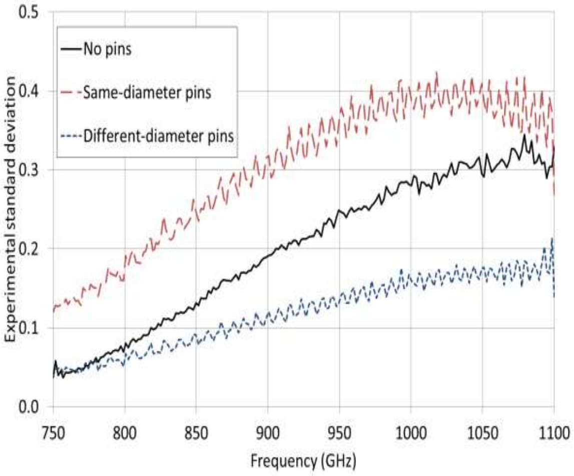

Fig. 9. $s(\Gamma^{IN}_{I_i})$ for the offset short-circuit

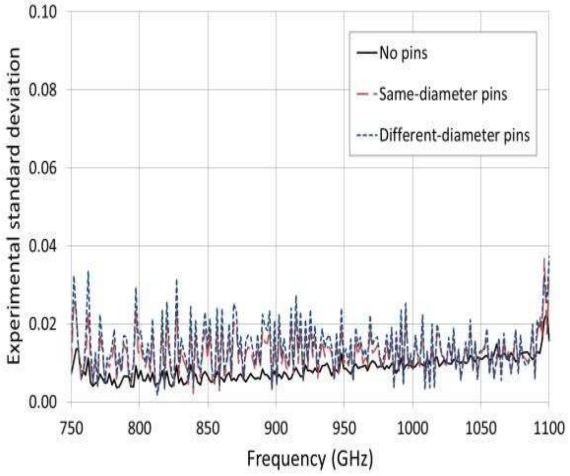

Fig. 12. $s(\Gamma^{IN}_{R_i})$ for the near-matched load

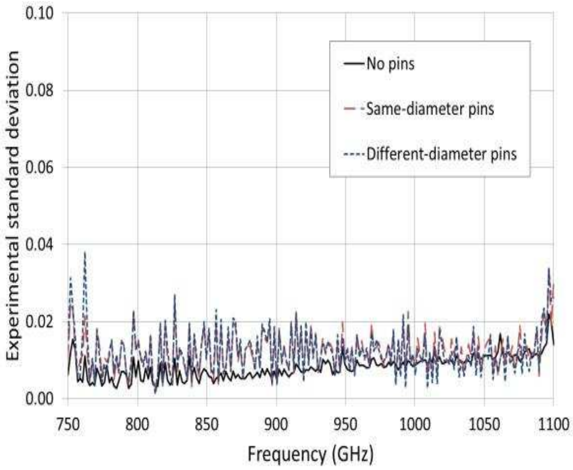

Fig. 10. $s(\Gamma^{N}_{R_i})$ for the near-matched load

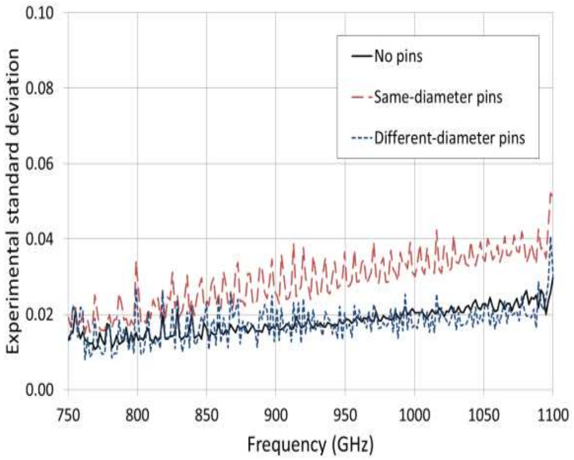

Fig. 13. $s(\Gamma^{N}_{I_i})$ for the near-matched load

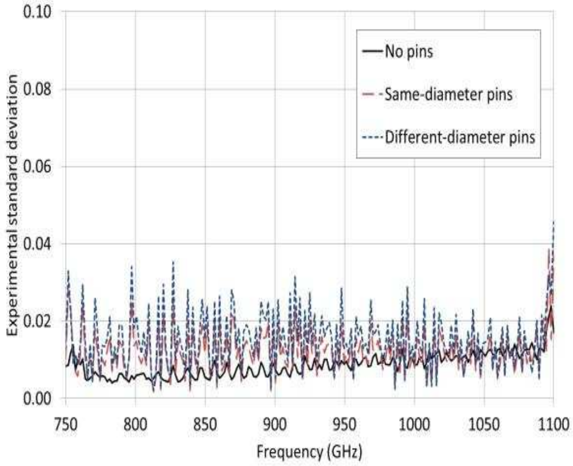

Fig. 11. $s(\Gamma^{I}_{R_i})$ for the near-matched load

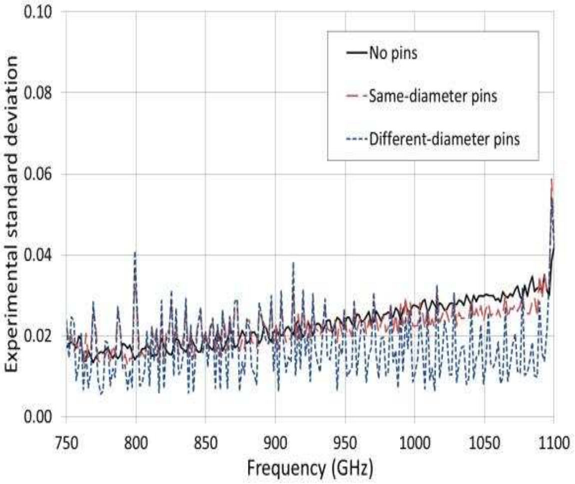

Fig. 14. $s(\Gamma^{I}_{I_i})$ for the near-matched load

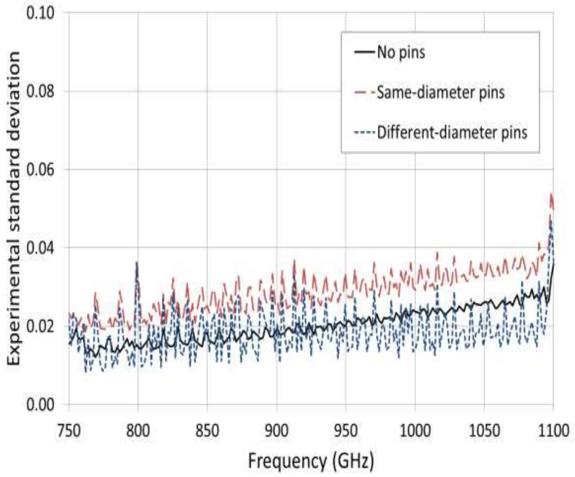

Fig. 15. $s(\Gamma_{I_i}^{IN})$ for the near-matched load

4. DISCUSSION

The results presented in Figs. 4 to 15 show that, for all three flange connection methods, there is no clear and obvious ‘best’ connection method (in terms of the achieved standard deviations due to the repeatability of flange connections) for the situations examined in this investigation. There are some instances (e.g. in Figs. 6, 9, 13 and 15) where the connection using same-diameter inner dowel pins exhibits inferior repeatability. However, there are also instances (e.g. in Figs. 4 and 7) where the same connection method performs as good as, or better than, the other methods. Similar types of observation could be made about the other connection methods. There are also instances where flange connection repeatability for all three methods appears to be significantly worse than for other instances – see, for example, Figs. 6 and 9. However, this type of behaviour has been explained in a previous investigation [2], where this effect was attributed to imperfect positioning of the flange alignment dowel pins and holes, and so the waveguide apertures of the DUT and the VNA test port will be misaligned (systematically) by different amounts, depending on the orientation used for the connection of the DUT.

Since all three methods achieve quite similar connection performance, it is instructive to examine the methodologies behind these types of connection. As mentioned previously, the relatively loose tolerances that make the conventional UG-387 flange design [4-6] unacceptable for use at high millimeter-wave and submillimeter-wave frequencies has led to two different strategies for improving this design:

1. Use tighter tolerance specifications for the outer alignment dowel holes and pins so that these holes and pins are suitable as the primary alignment mechanism for the flange;
2. Use inner alignment dowel holes and pins with relatively tight tolerance specifications as the primary mechanism for achieving the required alignment precision. For these designs, the loose tolerance outer alignment dowel holes and pins remain as legacy features of the flange, but do not play a significant role in the alignment process.

Table I summarizes the alignment properties for the conventional UG-387 flange design [4]. The table gives the specified range of diameter values for both the outer dowel holes and pins. These values are used to calculate a worst-case difference between these two diameters (i.e. between the largest hole-size and the smallest pin-size). This difference indicates how well the alignment pins fit the holes – the larger the difference, the worse the likely flange alignment. Table I shows a worst-case diameter difference for the UG-387 flange of 0.216 mm.

TABLE I
Diameters for the outer dowel pins and holes for conventional UG-387 flange

	Nominal (mm)	Tolerance (mm)	Range (mm)
Holes	1.702	+0.025, –0.000	1.702➞1.727
Pins	1.524	±0.013	1.511➞1.537
Worst case diameter difference between pin and hole: (1.727 – 1.511) mm = 0.216 mm			

Table II shows similar information for the outer alignment dowel pins and holes for the VDI flange type used during the investigation reported in this paper. This information is derived from values given in Fig. 3 (although the values in Fig.3 are specified in inches). Table II shows a worse-case diameter difference for this VDI flange of 0.092 mm, which is considerably better than the conventional UG-387 flange summarized in Table I.

TABLE II
Diameters for the VDI flange outer dowel pins and holes

	Nominal (mm)	Tolerance (mm)	Range (mm)
Holes	1.613	+0.008, –0.000	1.613 ➞ 1.621
Pins	1.537	±0.008	1.529 ➞ 1.545
Worst case diameter difference between pin and hole: (1.621 – 1.529) mm = 0.092 mm			

We can use a similar method to examine the alignment properties of the two connection methods described in this paper that used the inner dowel holes and pins. This information is shown in Tables III and IV for the ‘same-diameter inner dowel pins’ method and the ‘different-diameter inner dowel pins’ method, respectively. These tables show worse-case diameter differences of 0.046 mm for the same-diameter inner dowel pin method and 0.015 mm for the different-diameter inner dowel pin method. This would imply that the connection methods using the inner alignment holes and pins should provide better alignment than the use of the outer pins alone. However, the results from this investigation (in terms of achieved repeatability) suggest that the alignment provided by the tighter tolerance outer alignment dowel pins and holes for the VDI flange design is such that adding additional alignment mechanisms (i.e. using the inner alignment holes) does not improve significantly the overall alignment of the waveguide apertures. It therefore remains to be seen whether the connection strategy proposed in the new IEEE standard [7] (i.e. just using high-precision inner alignment holes and pins, along with loose tolerance outer holes and pins, as specified in the conventional UG-387 flange design) will result in improved connection repeatability compared to the repeatability performance obtained in this paper. The investigation of this type of connection strategy will need to wait until the flanges specified in the new IEEE standard [7] become available commercially and are used for waveguide components operating at these frequencies.

TABLE III
Diameters for the inner dowel pins and holes involved in the ‘same-diameter inner dowel pins’ connection method

	Nominal (mm)	Tolerance (mm)	Range (mm)
Holes	1.588	+0.013, –0.000	1.588 → 1.601
Pins	Measured (mm)		
	1.555 (and 1.556)		
Worst case diameter difference between pin and hole: (1.601 – 1.555) mm = 0.046 mm			

TABLE IV
Diameters for the inner dowel pins and holes involved in the ‘different-diameter inner dowel pins’ connection method

	Nominal (mm)	Tolerance (mm)	Range (mm)
Holes	1.588	+0.013, –0.000	1.588 → 1.601
Pins	Measured (mm)		
	1.586		
Worst case diameter difference between pin and hole: (1.601 – 1.586) mm = 0.015 mm			

5. CONCLUSIONS

This paper has presented a detailed investigation and analysis of the connection repeatability performance that can be achieved from using waveguide flanges that are currently available on VDI waveguide extender heads for VNAs in the WM-250 waveguide size.

The investigation has concentrated on assessing likely improvements in connection repeatability due to the use of the inner alignment dowel holes found on these flanges. The use of different sizes of dowel pin has been evaluated as part of this exercise.

The results show that, for the flange types manufactured by VDI, there is no clear advantage, in terms of the achieved connection repeatability, in using these inner alignment dowel holes when making connections with these flange types.

It remains to be seen whether the use of the flange design that is currently being specified in the on-going draft IEEE standard [7] will improve upon the connection repeatability observed during this and earlier investigations [1, 2].

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