

Design and RF Performance Validation of a New Miniature Rectangular Waveguide Flange for Millimeter-wave Frequencies and Above

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Abstract—A new miniature flange for interconnecting millimeter- and submillimeter-wave rectangular waveguide components has been developed by Flann Microwave Ltd. This paper reports on the design and RF performance evaluation of the flange, designated FSM-45. A rectangular waveguide calibration kit featuring the FSM-45 flange in the WR 6.5 band (also denoted WM-1651 or D-band) was subject to metrological evaluation by the UK's National Physical Laboratory whereby its key performance metrics, namely connection repeatability and interface reflection, were quantified. The results were compared with equivalent results, both measured and modeled, for the IEEE standardized 1785-2a flange, which is considered the current state-of-the-art. The outcomes reveal the exceptional performance of the FSM-45, and its suitability for deployment in RF technologies across the industry.

Keywords—rectangular waveguide, flange, interface, vector network analyzer, repeatability, reflection coefficient.

I. INTRODUCTION

Since the exploitation of the millimeter and sub-millimeter-wave bands of the electromagnetic spectrum has increased over the recent decades, manufacturers and users have overwhelmingly relied on the MIL-DTL-3922/67D flange [1] (often called UG-387), or variants thereof, to interface between rectangular waveguide components operating at 50 GHz and above. This flange has been the basis of all three standardized interfaces in the first edition of the IEEE 1785.2 standard for waveguide interfaces [2], which specifies interfaces for waveguides operating at 110 GHz and above. Reliance on this interface has imposed a minimum size requirement on component assemblies as the size of this interface - 19.05 mm ($\frac{3}{4}$ inch) in diameter - needs to be accommodated for every component interconnect. The UG-387 is widely adopted for waveguides operating at frequencies starting at 50 GHz. At this frequency, the waveguide aperture is in good proportion to the size of the guide. However, at frequencies above 100 GHz, the flange diameter is significantly larger than the size of the waveguide aperture. For instance, in the WR 10 (WM-2540) band (75 to 110 GHz) [3], the broad-wall dimension to flange diameter ratio is 1:7.5. At the WM-380 band (500 to 750 GHz) [3], this ratio is greater than 1:50. This ratio continues to increase exponentially into the THz bands.

Recently, a miniature flange has been developed by Flann Microwave Ltd, designated FSM-45 (see Fig. 1). This flange is suitable for components in millimeter and submillimeter-wave bands and has been demonstrated on a commercially available

millimetric waveguide switch [4]. This miniature flange has the potential to meet the widespread need in the RF industry for a flange with smaller footprint for integration into waveguide assemblies and subsystems (e.g., compact radar sensor modules, multi-channel mm-wave front ends, space-constrained subsystems for satellites and aerospace, mm-wave imaging systems, etc.).

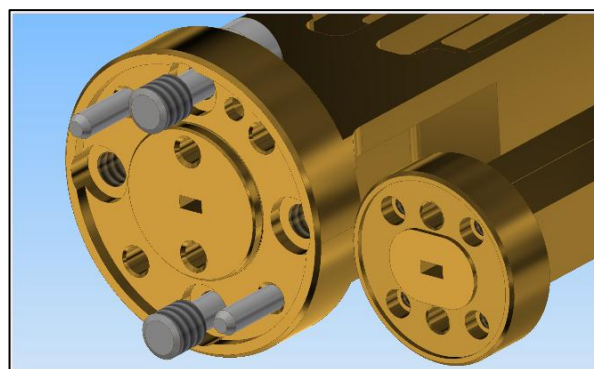


Fig. 1. IEEE 1785-2a flange (left) and the new FSM-45 flange (right).

To demonstrate suitability for widespread uptake by industry, rigorous flange performance evaluation with comparison to current state-of-the-art is necessary. This paper reports on such a study where evaluation of FSM-45 flange performance is carried out in the WR 6.5 [5] (WM-1651 [3]) waveguide size (110 to 170 GHz, i.e., D-band). This is a key band seeing widespread developments in 6G and other advanced connectivity technologies and will benefit from the availability of a fit-for-purpose miniature flange in better proportion to the size of the waveguide. In this study, calibration kit components fitted with FSM-45 flanges are analyzed for their repeatability and interface reflection performance [6]. These two performance metrics, being the dominant random and systematic effects affecting interface connections respectively, are compared with modeled results and those obtained from measurements of the current state-of-the-art, this being the IEEE standard 1785-2a flange [3].

This paper is organized as follows. Section II introduces the FSM-45 flange. Section III describes the connection repeatability evaluation. Section IV describes the interface reflection evaluation. Section V gives the conclusions.

II. THE FSM-45 FLANGE

The design of the FSM-45 flange is shown in the engineering drawing in Fig. 2. Its key features are a 12 mm outer diameter, a stadium-shaped boss and mounting holes in each corner. The mounting screws are size M1.6. The location holes for the inner alignment dowels are consistent with the IEEE 1785-2a flange and so its nominal alignment tolerances are expected to be at least as good. If desired, the two types of flange can be mated by means of an external clamping mechanism. Short flange-to-flange adapters are also available. It is recommended to use the FSM-45 for WR 10 waveguide sizes and smaller. As an example, Fig. 3 shows a photograph of the flange in the WR 6.5 waveguide size. With a reduced surface area compared with UG-387 type flanges, the same clamping force gives ~60% increase in contact pressure between mated interfaces. Furthermore, the alignment is governed exclusively by the inner precision dowels which has the potential to provide performance advantages.

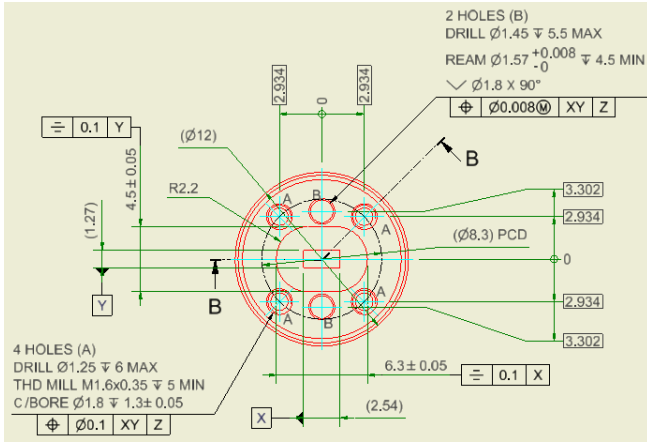


Fig. 2. Engineering drawing of the FSM-45 flange.

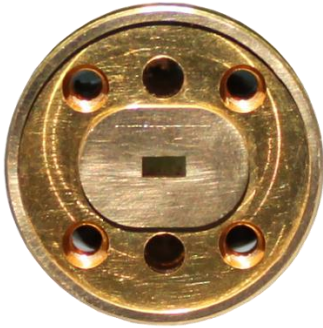


Fig. 3. Photograph of the FSM-45 flange in the WR 6.5 size.

III. FLANGE CONNECTION REPEATABILITY EVALUATION

A. Method

The connection repeatability of an interface arises from the mechanical tolerances of the connection mechanisms used to connect the interface to another of its kind. It is a key performance metric which quantifies its in-use reliability, and therefore, its suitability as a standardized interface for

interconnecting high frequency components. Procedures for assessing repeatability in a metrologically sound manner are provided in documents such as the EURAMET VNA calibration guide [7], the IEEE standard for coaxial connectors [8], and specifically for rectangular waveguides, the IEEE 1785.3 standard [9] and good practice guidance from renowned international experts [10]. Based on this guidance, the following method for connection repeatability evaluation was employed:

1. n measurements (where n is suitably large, e.g. 8) of the reflection coefficient Γ of a device under test (DUT) at each frequency f are gathered using a calibrated vector network analyzer (VNA) with a high-quality test port.
2. The standard deviation s of the n independent real and imaginary parts of Γ (s_{re} and s_{im}) are calculated per f .
3. The vectorial magnitude $s_{mag} = \sqrt{s_{re}^2 + s_{im}^2}$ is taken to represent the linear s of the dataset, per f .
4. This is then expressed in dB at an equivalent 95% level of confidence (coverage factor $k = 2$), per f , as follows:

$$r = 10 \cdot \log_{10} (2 \cdot s_{mag})^2 \quad (1)$$

Using (1), the flange connection repeatability is summarized as a single value per frequency. The logarithmic format is helpful for facilitating analysis and comparison of different sets of results each having small magnitudes.

B. VNA calibration, DUTs & measurement practice

To gather the required data to evaluate the connection repeatability of the FSM-45 flange, a suitable VNA is required. To this end, specialized test port adapters were fabricated to adapt from the standard 1785-2a flange to the new FSM-45 flange. These are shown in Fig. 4. With these test port adapters fitted to VNA frequency extenders and a suitable calibration performed, measurements can be carried out with a reference plane at the FSM-45 interface. In addition, as noted in [7], the quality of the test port interface is required to be at least as good as the measured DUT in order to gather meaningful connection repeatability data.

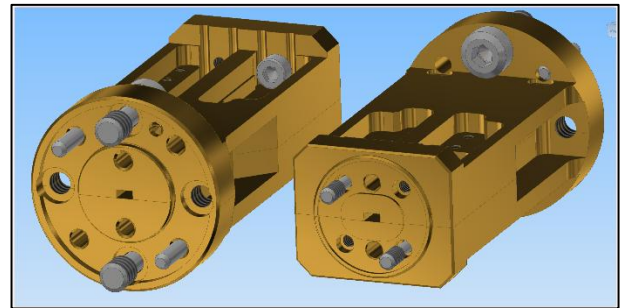


Fig. 4. 1785-2a to FSM-45 VNA test port adapters. Left: 1785-2a end; right: FSM-45 end.

For the repeatability evaluation, a VNA calibration should be performed with suitable standards. Following calibration, the repeatability of DUTs as well as the standards themselves can be assessed, as any variation in their reflection response due to repeatability will be observed through repeat connections.

Overall, a flush short-circuit, two $\frac{3}{4}$ -wave offset shims and a matched load, all fitted with the FSM-45 flange, were used as standards in this study. The repeatability of both 1- and 2-port FSM-45 DUTs was evaluated using the method described previously. In the 1-port case, a Short / Offset-short / Offset-short / Load (SOOL) calibration was performed. The Offset shorts were constructed by cascading each of the offset shims with the flush short-circuit. In the 2-port case, a Line-Reflect-Line (LRL) calibration was performed. With the VNA test port in fixed position, the 1-port case has the advantage of being free from the impact of any cable movement. Movement of the VNA test port 2 is necessary for 2-port measurements, and so it is expected that this will have some impact on the 2-port results.

It is necessary to evaluate the repeatability on multiple instances of the flange in order to obtain a meaningful characterization of the flange performance, i.e., providing results that are truly representative of the flange in general, rather than in specific cases. To this end, a variety of 1-port and 2-port DUTs including offset shims, matched terminations, straight waveguides and flush short-circuits, and combinations thereof, as well as thru connections of the two FSM-45 VNA test ports were measured. A common set of 1785-2a-style inner alignment dowels [2] were used for all connections, as was an adjustable torque driver set to apply 12 cNm (18 Ozf.in) torque. These steps serve to minimize any differences in results due to connection mechanisms and torque levels. It has been noted in several studies that gravitational bias can affect horizontally mounted waveguide device connections [6] [10]. Vertically mounted VNA setups can serve to mitigate this effect, however, this approach discounts the potential for 2-port measurements and is less representative of the in-use performance of flanges seeing as horizontal mounting is the conventional orientation of waveguide connections. For these reasons, a conventional horizontally mounted setup was used in this study. Typically, between 8 and 10 repeat reconnections were measured, which was deemed adequate based on the variation observed in the results. Two further sets of measurements were gathered to characterize the limits of the measurement system due to: i) system noise, by performing repeat measurements of a load without reconnection; and ii) cable movement, by performing repeat measurements of a Thru without reconnection, and with a small amount of movement of the VNA extenders between each measurement. The repeatability from these two sets of measurements acts as the ‘best-case’ repeatability performance of the 1-port and 2-port repeatability results, respectively.

C. Results and analysis

A selection of the results of the connection repeatability evaluations is plotted in Fig. 5. For comparison, results for the standardized 1785-2a flange, both measured and modeled, are also shown. The 1785-2a measurements were carried out using the same method as detailed in Section III with a Flann WR 6.5 matched load on the same VNA fitted with a 1785-2a test port. Modeled results were generated using methods provided in the IEEE 1785.3 standard [9], accounting for the effect of the mechanical tolerances of the interface and connection mechanisms giving rise to E-plane, H-plane and angular misalignments. The effect of each misalignment on the

reflection coefficient of the interface is modeled using a suitable method, and these are combined linearly. Evidently, the FSM-45 achieves very good repeatability performance. In the worst case, the results are equivalent to the 1785-2a standard, and in the best case, equivalent to the system noise (i.e., the effect of reconnection was indistinguishable from the effect of random system noise, at certain frequencies). As expected, the best-case performance of the 2-port Thru DUT is determined by the Noise + cable movement results, and the DUT and best-case results show close agreement.

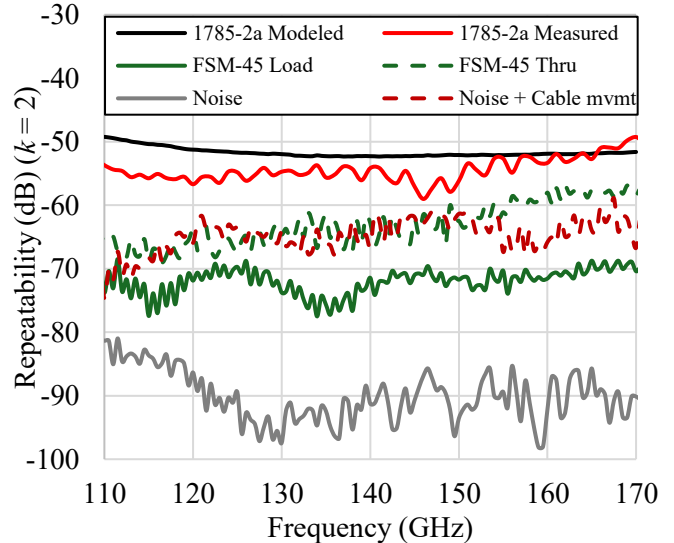


Fig. 5. Results of the connection repeatability evaluations for both 1- and 2-port FSM-45 flanged DUTs, compared with 1785-2a (both measured and modeled). Noise and Noise + cable movement represent ‘best-case’ repeatability performance of the 1-port and 2-port results, respectively.

IV. INTERFACE REFLECTION EVALUATION

The interface reflection quantifies the magnitude of the reflection coefficient, $|\Gamma|$, arising at the junction of a pair of mated interfaces. This is a systematic reflection affecting all connections of the flange and is therefore another key performance metric of waveguide flanges. This quantity is challenging to measure directly without the influence of other aspects of the measured device(s). Therefore, two methods were devised and applied here to achieve this measurement:

- LRL calibration: two $\frac{3}{4}$ -wave shims with $\lambda/4$ phase separation are used in an LRL calibration, leaving the zero-length Thru (i.e., direct connection of the two VNA test ports) to be measured as a DUT. The resultant $|\Gamma|$ quantifies the magnitude of interface reflection.
- Time-gating: Following calibration (1-port or 2-port), the $|\Gamma|$ of a device (in this case, a matched termination) is transformed to the time-domain. The reflection peak at the test port interface (i.e., $t = 0$) is time-gated and transformed back to the frequency-domain. The magnitude of the reflection at the interface is thereby isolated from contributions arising from other features of the DUT.

With LRL providing high accuracy but reliant on the quality of the Line standards, the time-gating method provides a

complementary approach which works on entirely different assumptions. The results for the interface reflection evaluation of the FSM-45 flange using these two methods are shown in Figs. 6 and 7, respectively. In both cases, modeled $|\Gamma|$ results with 95% confidence intervals are shown for comparison, again generated using IEEE standard 1785.3 methods [9].

The $|\Gamma|$ results from the FSM-45 Thru connection shown in Fig. 6 show magnitudes lower than the measured results for the 1785-2a flange and in agreement with the 1785-2a modeled results across almost the entire band. Fig. 7 shows time-gated results for an FSM-45 matched termination and an equivalent 1785-2a DUT (i.e., a WR 6.5 matched termination from Flann Microwave) measured on a conventional 1785-2a VNA test port and following a suitable calibration. The FSM-45 shows lower reflection than the 1785-2a across most of the band, and equivalent to the 1785-2a modeled results throughout.

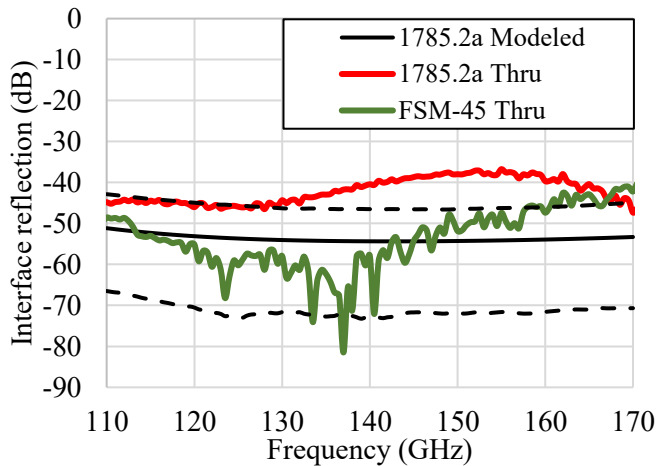


Fig. 6. Interface reflection evaluation results using the LRL calibration method comparing FSM-45 and 1785-2a Thru connections as DUTs. Modeled 1785-2a $|\Gamma|$ results are shown by a solid black line, with the 95% confidence interval shown by the dashed black lines.

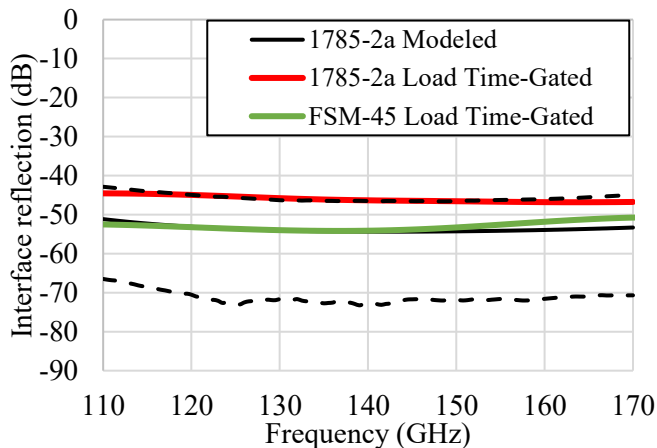


Fig. 7. Interface reflection evaluation results using the time-gating method. Measured $|\Gamma|$ of matched loads with 1785-2a and FSM-45 flanges are each time-gated to isolate the reflection at the interfaces with their respective VNA test port. Modeled 1785-2a $|\Gamma|$ results (black solid line) are shown for comparison, with the 95% confidence interval shown using black dashed lines.

It is evident from all reported results that the FSM-45 provides advantages over the UG-387 style flanges beyond its miniature form factor. A combination of factors including the reduced surface area, resulting in increased contact pressure between a mated pair of interfaces and reduced mechanical moment arm, as well as the lack of outer alignment pins, which can potentially interfere with the precision inner alignment mechanisms, all serve to improve electrical performance of the FSM-45 over and above the current state-of-the-art.

V. CONCLUSION

This paper has reported on the design and metrological evaluation of a new miniature rectangular waveguide flange, designated FSM-45. This flange is designed as an interface for millimeter and sub-millimeter-wave waveguide components. Comparison with the current state-of-the-art, i.e., the IEEE standardized 1785-2a flange, in the WR 6.5 band showed the superior performance of the FSM-45 flange in multiple instances in terms of connection repeatability and interface reflection. The outcomes of these evaluations demonstrate the suitability of this interface for deployment in high-frequency systems where there is demand for a waveguide interface with a smaller footprint.

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