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ABSTRACT

We have designed, constructed, and tested an electrical vacuum feedthrough that can carry a large number of microwave signal lines, has high vacuum compatibility, and is highly customizable. We found that it had a leak rate of approximately 10^{-7} Pa L/s (7.5×10^{-9} torr L/s), making it suitable for high-vacuum systems such as cryostats. The feedthrough is low-cost, and the printed circuit board-based design allows the choice of any surface-mountable microwave connector. We additionally verified operation through consistent use on a real cryogenic system and verified the mechanical robustness of the feedthrough.

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I. INTRODUCTION

A wide variety of vacuum applications require electrical signals to be carried into and out of the vacuum system. These electrical signals, such as sensor voltages or bias currents, frequently benefit from being carried on a microwave transmission line, either as a means to increase signal bandwidth or to reduce coupling to noisy environments. Unfortunately, passing a large number of microwave electrical signals through a vacuum feedthrough can be expensive and often requires a large area on the surface of the vacuum chamber. Additionally, the choice of feedthrough connector is often significantly limited, with the vast majority of available hermetic connectors falling into one of two categories: individual microwave connectors such as (Sub-Miniature version A) connectors or parallel-pin varieties such as D-subminiature connectors.

Individual-connector microwave vacuum-feedthroughs work very well: they often have extremely good vacuum ratings (suitable for ultrahigh vacuum)[1] and are typically well-grounded to the vacuum chassis, which prevents stray RF radiation from the ambient environment from inadvertently entering the system. However, these connectors are often expensive and space-inefficient. For instance, in cryogenic vacuum systems, arrays of SMA feedthroughs are often used to communicate with the devices under test,[2,3] but they have a very low packing density—on the order of 1 connector/cm^2. Additionally, ultrahigh vacuum ratings are often unnecessary—again in the case of cryogenics, a vacuum rating below ~10^{-4} (Pa/L)/s [~10^{-6} (torr/L)/s] is usually unnecessary, thanks to the cryopumping effect.[4,5] Other connectors such as D-subminiature types are capable of reaching much higher packing densities,[6] but are of typically low-bandwidth (<100 MHz) and not impedance-matched to the internal cabling.

To simplify the process of getting electrical signals into and out of a vacuum system, we have designed, constructed, and tested a high-density, high-vacuum feedthrough from inexpensive and readily available components. This feedthrough allows for any kind of microwave connector to be used, creates an excellent vacuum seal of 10^{-7} Pa L/s (7.5×10^{-9} torr L/s), has strong mechanical support, and is easy to build and customize.

II. OVERVIEW OF COMPONENTS

The feedthrough consists of two primary components: a flange and a set of printed circuit boards (PCBs). The flange is what creates the vacuum seal between the environment and the cryostat—it acts as a removable interface between the vacuum system and the outside world. Additionally, it has four machined slots which hold the PCBs. The PCBs were 4-layer boards designed to carry microwave signals with minimal crosstalk and were fabricated by an external company using the most basic process with no special modifications. Both the flange and the PCBs can be designed independently according to users' needs—the only requirement is that the flange be mechanically sturdy enough to support the slots cut into it, which should be true for most standard vacuum flange types.

A. The flange

Although this type of feedthrough could be constructed from a number of vacuum flange types, in the vacuum feedthrough described here, we used a brass KF50 blank, which was suitable for our cryostat. KF flanges are typically less expensive than other vacuum flange variants such as conflat and are ideal for medium- to high-vacuum applications which are common in cryogenics. Brass is also easy to solder without special flux and can be machined easily, which simplifies the construction process. The design of the flange is simple: as shown in Fig. 1, the flange is just a brass KF50 blank with 4 slots machined in it. The slots are cut to be just wider than the width and thickness of the PCB to allow effective mechanical and electrical coupling between the PCB and the flange. They were spaced such that the four PCBs (with microwave connectors) could be stacked vertically. We note that the slots were offset with respect to the center of the flange—in this setup, the PCBs had connectors only on one face, so offsetting the slot locations allowed the entire assembly to be centered with respect to the internal KF50 tubing volume inside the cryostat.

B. The PCB

The design of the PCB is also customizable to the application, but for this particular implementation, we used a 4-layer board with a high-density microwave connector on each end. The construction of the board was outsourced to an inexpensive fabrication facility, was made from 1.6 mm thick FR4, and had 36-μm-thick copper. The board carried microwave signals on one of the internal copper layers and used the outermost layers as ground planes, creating a 50 Ω microwave strip line configuration. As shown in Fig. 2, the strip line signal conductor had a trace width of 0.3 mm, and the ground planes were 1.2 mm and 0.2 mm from the signal plane. In total, each PCB carried 10 microwave lines that were connected in the ground-signal-ground (GSG) style to the high-density microwave connector. The microwave connectors that we used on the PCB were Samtec FCS8-20-01-L-S-A-TR micro-coax-assembly connectors. We used via-fencing[7] between signal lines to minimize crosstalk between neighboring signal lines and to electrically couple the outer ground planes together. Microwave transmission and reflection measurements for the PCB are shown in Fig. 3.

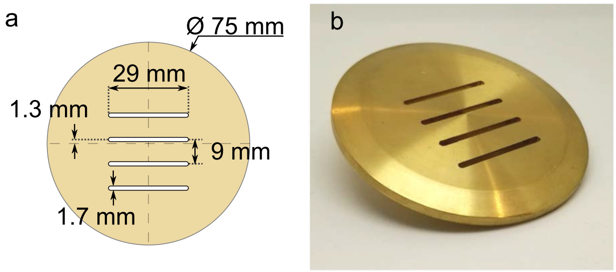

FIG. 1. Flange used in the assembly of the feedthrough machined from a blank KF50 flange. (a) Mechanical specifications of the flange showing the four slots machined through the blank flange. Note that the slots are shifted off-center so that the whole assembly is centered when the microwave connectors are added to one side of each PCB. (b) Photograph of the KF50 flange after slots have been machined into it.

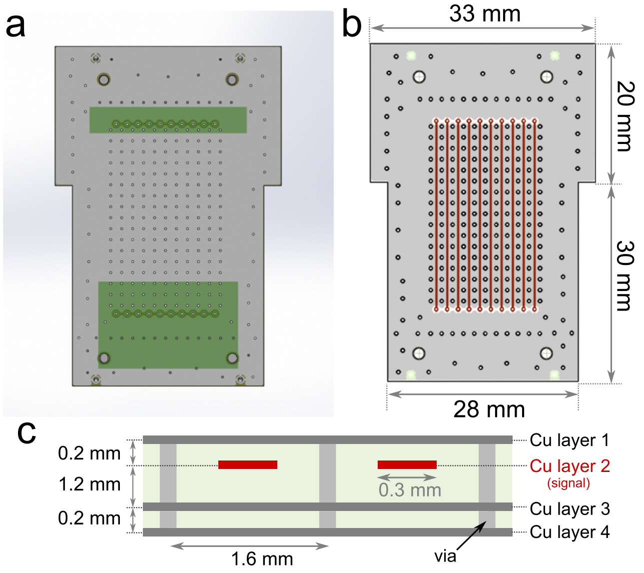

FIG. 2. Layout of the 4-layer PCB used to carry electrical signals through the vacuum feedthrough. (a) The outer layers of this 4-layer board acted as a ground for the signals and soldering points. (b) Cutaway of the top ground layer showing the inner layer with the 10 strip lines (RF signal lines shown in red). (c) Cross-sectional view of microwave lines showing the 50 Ω strip line configuration in a standard 4-layer board.

One fixed requirement for the feedthrough assembly is that the outermost metal layers of the PCB must be solid, bare copper in the vicinity where the PCB is attached to the flange—this is necessary to solder the board directly to the flange. Soldering the board to the flange creates a strong mechanical connection and additionally prevents RF leakage through the flange along the edge of the PCB. As an additional precaution, we also made the PCB into a T-shape, with the wider end on the ambient-pressure side. This shape helped ensure

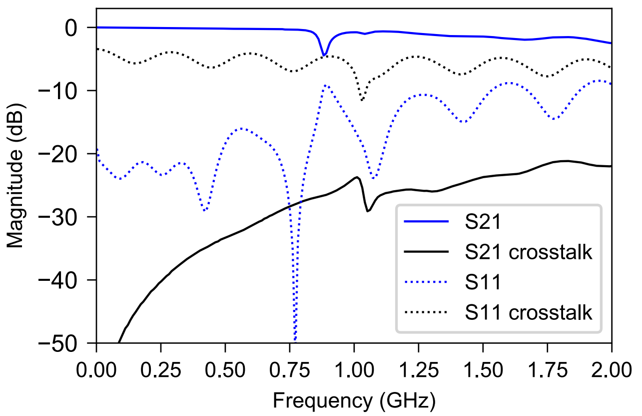

FIG. 3. Microwave transmission and reflection measurements of the feedthrough PCB. Crosstalk measurements were made using adjacent signal traces. The S_{21} insertion loss is 0.2 dB at 500 MHz and 1.45 dB at 1.5 GHz.

that the PCB was mechanically supported against the force from the pressure differential. It is additionally assisted with positioning during assembly. Aside from the T-shape and solderable ground planes, design of the PCB is very flexible: any connector and signal-line configuration can work. For instance, if higher density connections are needed, a PCB with six or eight metal layers could be used along with a multi-row microwave connector.

III. ASSEMBLY

A. Attaching the microwave connectors

The assembly of the feedthrough began by soldering the microwave connectors to the PCB, which happened in two stages. In the initial stage, the exterior (air-side) connectors were soldered to the PCBs using standard 63:37 tin–lead solder paste with a melting point of 183 °C. In the second stage, the PCBs were slotted loosely into the flange—note that since our boards were single-sided, up/down orientation mattered in addition to ensuring that the wider end of the T-shaped PCB was on the ambient-pressure side of the flange. A stencil was then used to apply solder paste (also 63:37 tin–lead) to the pads of the interior (vacuum-side) microwave connectors, and the connectors were placed into position. We found that occasionally, the solder filling the mounting holes of the microwave connectors would drip and attach the board to whatever is beneath it, so it is advisable to clear out excess solder on the bottom before baking. Once ready, the whole assembly was loaded into an oven and heated to melting (200 °C). For our purposes, we found that an inexpensive electric toaster oven was large enough to accommodate the flange and thermally stable enough to melt the solder as desired. Once the assembly had cooled, the microwave connectors were tested for electrical connectivity and unwanted electrical shorts. Note that at this point in the process, the PCBs were still loose inside the slots—the PCBs are fixed to the flange in the following steps. Although we typically had success in soldering all the PCBs in a single baking step, once all the connectors were baked, it became difficult to correct the occasional soldering error due to the tight spacing of neighboring PCBs. We found that a more robust method was to perform the stenciling/baking for one board at a time; this allowed the testing and correction of each successive board. This process is displayed in Fig. 4(b). The repeated heating and cooling of the assembly did not have any apparent impact on the vacuum properties of the feedthrough.

B. Soldering the PCB to the flange

The PCB was soldered directly to the flange using rectangular brass bars as supporting structures. As shown in Fig. 4(c), the brass bars were cut to the length of the PCB and ultimately soldered in place, guaranteeing that the PCB and the flange had a large amount of direct mechanical stability. This solder joint also formed the bulk of the vacuum seal and helped isolate the inside of the vacuum chamber from external electrical noise. While soldering them to the flange, the PCBs were supported so that the external connectors were on top and the PCBs were fully seated in the slot. Before applying the solder, we prepared the surfaces by lightly sanding all areas that were going to be soldered with steel wool or sandpaper—this included the top surface of the flange, the sides of the brass bars, and the outer metal layers of PCBs. Sanding these areas helped ensure that the surfaces were clean and that the solder was able to wet all the components. Once prepared, we applied a 1-mm-thick bead of inexpensive low-temperature solder paste (Sn-42%/Bi-57%/Ag-1%, 137 °C melting point) to the edges between the PCBs and the flange, highlighted in Fig. 4(c). A low-temperature solder was used so that when the assembly was baked, the solder could be melted without affecting the microwave connector joints. After the solder paste was applied, the brass bars were firmly pushed into the paste such that excess paste was squeezed out along the length of the bar. We found that no external clamping of the bars was necessary to keep the bars from moving after placement—the viscosity of the solder paste kept them positioned correctly until baking. However, excess solder paste around the bars should be cleared, as the wetting action during baking could occasionally cause the rods to float out of position. With the brass bars in place, we then baked the assembly at 160 °C for 15 min to melt and wet the low-temperature solder. The long bake time was required to heat the large thermal mass of the brass flange. After cooling, we then performed another round of visual and electrical tests to verify that electrical connections were intact. Typically, we did not find any errors, but occasionally excess solder would drip through the flange slot and short wires on the male connector. We ameliorated this by tying copper solderwick around each PCB before baking in order to catch any droplets of excess solder.

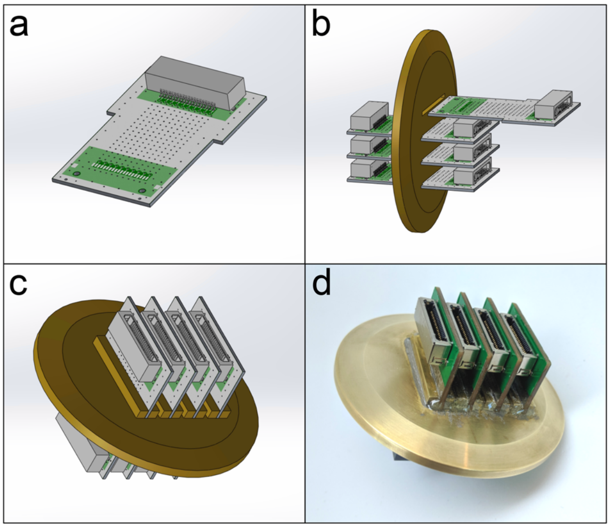

FIG. 4. Assembly diagram for the feedthrough. (a) The PCBs are partially assembled with one microwave connector soldered to each PCB with 63:37 tin–lead solder. (b) The partially assembled PCBs are added one at a time to the flange, and the second microwave connector is soldered into place. (c) The brass bars are placed at the intersections of the PCBs and the flange and soldered into place with a low-temperature solder. (d) Photograph of the final assembled feedthrough.

C. Finalizing the flange

The final step of the feedthrough construction was to seal the assembly with epoxy, which has historically been used to fill holes in feedthroughs.[8] The soldering process creates a strong mechanical support, but inevitably leaves pinholes in the area surrounding the slots which need filling. By applying epoxy to the external (ambient-pressure) side of the assembly, we were able to fill these pinholes and create a vacuum-tight seal. We began the sealing process by again lightly sanding the surfaces of the ambient-pressure side, specifically any areas which contained a seam between the flange, PCB, or brass bars. These areas included the surfaces of the PCB near the brass bars, the surface of the flange near the brass bars, and the areas around the edges of the PCB. We then prepared the epoxy, loaded it into a syringe, and liberally applied it to the sanded seams, with special attention paid to filling the small gap remaining at the ends of the slots which the PCBs did not completely fill. We found that inexpensive 5-min epoxy was sufficient for our cryogenic applications, but for applications more sensitive to outgassing, it may be prudent to use a vacuum-compatible epoxy. After the application of the epoxy, the board was allowed to cure for an hour, after which it was tested for leaks using a helium leak-checker or, alternatively, a turbopump with a vacuum gauge attached. If leaks of above ~10^{-5} (Pa/L)/s were found, we applied another layer of epoxy and re-tested the vacuum properties.

IV. RESULTS AND ANALYSIS

A. Helium leak checking

To verify that the feedthrough was vacuum compatible, we ran two standard vacuum tests: (1) we measured the leak rate with a helium leak checker and (2) we placed the feedthrough on the end of a turbomolecular pump and measured the resulting vacuum pressure. For the first test, we filled a plastic container with helium and placed the external portion of the flange inside it, in order to fully immerse the flange in helium. We filled the container once and left it sealed, observing the leak rate over time. Shown in Fig. 5 is a graph of the helium leak rate over time for a completed flange and for a blank (solid brass) flange for reference. In that data, the blank flange shows a higher leak rate than the feedthrough, which is likely due to the experimental setup—the O-rings may have been seated slightly differently between the two experiments, causing a minor difference in baseline leak rate between the blank and feedthrough.

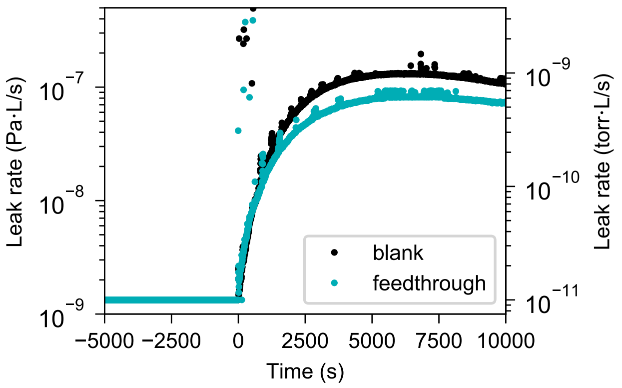

FIG. 5. Plot of helium leak rate vs time for a flange prepared according to the above procedure and a blank flange for reference. First, the leak checker was run with no helium applied for approximately 19 h to achieve a baseline measurement. Then, at time zero, helium was added to the environment. The primary source of helium leakage is likely through the apparatus O-ring, since the leak rate between the blank metal flange and the feedthrough is approximately equal. The higher leak rate from the blank flange is likely due to a small amount of leakage through the flange O-ring.

In order to allow the leak rate to settle, we attached the flanges to a leak checker for approximately 19 h. After the baseline measurement without helium was established, we then added helium to the container. The results are shown in Fig. 5. It can be seen that the performance of a completed feedthrough is comparable to that of a blank flange; both experience an increase in leak rate by approximately 10^{-7} Pa L/s (7.5×10^{-9} torr L/s) when the container is filled with helium. The leak checker can only detect leaks of magnitude greater than 1.33×10^{-9} Pa L/s (10^{-11} torr L/s), so the flat portion of the graph prior to helium application is an upper bound of the leak rate. Momentary spikes on the graph are an artifact of the helium leak checker apparatus, as they are present for both the feedthrough and the solid-metal blank flange. The eventual decline in leak rate after the addition of the helium is due to the seepage of the helium out of the test apparatus, which slowly reduces the ratio of helium to atmospheric air in the test setup. As suggested by the data, this flange should be acceptable for use in high-vacuum systems. We note, however, that this test does not account for generalized outgassing—this variety of feedthrough should not be used in environments where typical PCB outgassing would be unacceptable unless further work was done to seal the PCB, for example, by plating the PCB edges, using low-outgassing board materials, or by applying a low-outgassing conformal coating.[9,10] Plating the PCB edges may also make it possible to avoid the final epoxy step entirely, although micro-pinholes may still be present in the solder, so a final coating step would still be advisable. As a practical measurement, we also placed the feedthrough on the end of a turbopump. After pumping for 30 min, we found a base pressure of 9.3×10^{-6} Pa (7.0×10^{-8} torr). For reference, a blank flange had a base pressure of 1.01×10^{-5} Pa (7.6×10^{-8} torr) after pumping for 30 min, so again the feedthrough showed comparable vacuum performance to a solid-metal blank flange.

B. Mechanical stability

Also of importance when building a feedthrough is its mechanical stability, especially if the system requires frequent connection/disconnection of the microwave connectors. As a means of verification, we performed some rudimentary mechanical measurements to quantify the resiliency of the devices—we note anecdotally, however, in over a year of persistent usage on a cryogenic system (connecting and disconnecting connectors multiple times per week); we have not experienced a mechanical failure or vacuum leak in any of the multiple flanges we have built. To test the stability, we applied force to the PCBs while pumping on the feedthrough with a turbomolecular pump. We applied 98 N (a 10 kg weight) to the PCBs in four directions corresponding to normal and shear forces. We did not find failures of any kind, either mechanical or vacuum-based.

V. CONCLUSION

We have designed an electrical vacuum feedthrough with high packing density, mechanical robustness, high vacuum compatibility, and a wide scope of customization. This flange design is not limited to a particular size or the number of slots or type of connector, but is rather a general method for creating a vacuum feedthrough that can be affixed to any vacuum system. The flange is ideal for researchers who require flexible microwave connectivity without great expense. Additionally, the assembly of the feedthrough took only a few hours and was able to be replicated by undergraduate researchers. Future improvements may include plating the edges of the PCB with metal or using conformal coatings to prevent potential outgassing from the PCB material.

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