

Immersion Cooling Fixture for High Power Testing of Planar Microwave Transmission Lines

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Abstract—This paper introduces a test fixture for liquid cooling of two-port planar microwave transmission lines under high power operating conditions. A rectangular waveguide (RWG) feed followed by a non-contacting transition to the planar line is used to avoid end-launch connectors and other potentially power-limited connections. The fixture is fabricated using fused deposition modeling (FDM), and its interior RWG walls are coated with silver paint. The cooling test fixture is demonstrated herein using a through coplanar waveguide (CPW) fully immersed in a liquid coolant and measured in the 3–6 GHz frequency range. Non-intrusive distributed temperature measurements using an optical fiber sensor are also presented for the CPW line operated at high power. The entire structure has a minimum insertion loss of 1.6 dB at 3.6 GHz and 2.2 dB at 4.4 GHz with and without the liquid coolant, respectively. The fixture supports active cooling, and has minimal loss, accounting for less than 1.4 dB of the total insertion loss without the coolant, which confirms its viability for high-power testing.

Index Terms—Interconnects, Thermal Management, Liquid Cooling, Test Fixture

I. INTRODUCTION

Planar transmission lines are widely used in RF and Microwave circuits due to their low cost and ease of integration with other communication system front-end components. Some of the most commonly used planar transmission lines are microstrip lines, striplines, and coplanar waveguides (CPWs).

With the increasing power handling requirements for RF systems, thermal management has become an active area of research. This includes investigations on the power handling of planar lines [1]–[4], as the heat generated due to losses in the line may limit the maximum power handling capacity of the system [5]. Researchers have suggested ways to improve the power handling capability of planar transmission lines, such as careful material choice [6], thicker metallization [7], or using static cooling [8]. However, the authors are not aware of any publications on active liquid cooling of planar transmission lines. Therefore, this paper introduces a novel test fixture for such lines, specifically CPWs, that are operated at high power levels and cooled with an actively flowing liquid. The fixture can also accommodate cooling from different fluids in both natural and forced convection (static and active cooling) cases.

The fixture allows the line under test (LUT) to be fully immersed in a cooling liquid and avoids end-launch connectors. The complete immersion of the line eliminates complications

in the design which would exist under partial immersion conditions, in which case the characteristic impedance and propagation constant would change between the immersed and non-immersed portions of the line. More importantly, end-launch connectors and non-immersed portions of the LUT will experience significant heating and are susceptible to failure under high power test conditions, which was noted as a limitation of the setup in [8]. These challenges are resolved in the new design by using coaxial-fed rectangular waveguides (RWGs) that include non-contacting transitions from the RWG sections to the fully immersed LUT. The fixture also integrates easily with optical fiber sensors for non-intrusive distributed temperature measurements directly at the immersed LUT. This fixture is compatible with passive planar networks and can be adapted to include DC feedlines for active components. For brevity, this paper only shows a through CPW line; however, this work is foundational to future research on the cooling of planar transmission lines and planar RF systems in general.

The design and fabrication of the test fixture are presented in Section II. In Section III, measurements for a CPW inside the test fixture with and without static liquid cooling are discussed, and CPW temperature measurements using an optical fiber are shown. The paper is summarized in Section IV.

II. FIXTURE DESIGN AND FABRICATION

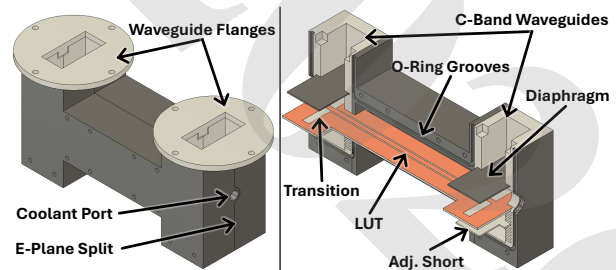


Fig. 1: 3D-model of test fixture's exterior with the metallized flanges, and its interior structure with the CPW and transitions.

The test fixture is shown in Fig. 1 from the outside and with one part of the split-block RWGs hidden. The fixture consists of RWGs used as feedlines, transitions from the RWGs to a planar transmission line, which in this case is a CPW, and an

adjustable backshort for tuning. The fixture also has coolant ports at both ends, a diaphragm to prevent upflow, and grooves to house o-rings and support the suspended LUT and other components.

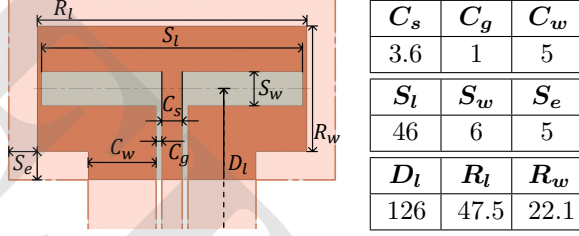


Fig. 2: CPW and transition dimensions in mm .

The RWG-to-CPW transition is based on [9] and is shown individually in Fig. 2, where all the CPW and transition dimensions are summarized. The CPWs were designed to have a characteristic impedance of 75Ω when in air. The substrate is Rogers RO4003C with a dielectric constant of 3.55 and thickness of $1.4 mm$. The RWGs feeding the transition are standard WR-187 with inner dimensions $R_l \times R_w$. Thus, only the darker colored part in Fig. 2 obstructs the RWGs, whereas the remainder of the transition extends by a distance of S_e into the grooves in the fixture walls in order to support the suspended LUT.

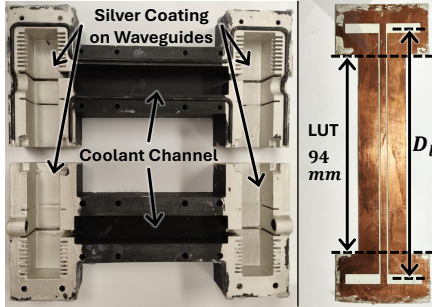


Fig. 3: 3D-printed test fixture with split-block RWGs and coolant channel, as well as LUT and transitions.

The fabricated components are shown in Fig. 3. The test fixture was made with polylactic acid (PLA) using an FDM printer, and the RWG sections and flanges were hand-painted with silver ink. The CPW and transitions were milled using a desktop computer numerical control (CNC) machine. To begin testing, the LUT was inserted into the fixture, the adjustable backshort seen in Fig. 1 was changed to $30 mm$ from the CPW substrate, and the two parts in Fig. 3 were joined. Due to inaccuracies from hand-painting the conductive ink, milling, and 3D-printing with low-tolerance equipment, this fabrication process is not viable at higher frequencies, but results in the next section show that it is acceptable in the $3-6 GHz$ range.

III. RESULTS & DISCUSSION

A. CPW Measurements in Fixture

Measurement results shown in this section were obtained using an Agilent N5227A network analyzer after a two-port

coaxial calibration, such that the S-parameter reference planes are at the coaxial port of the coax-to-RWG adapters that connect to the test fixture, and therefore include all transition effects. All simulations were done in AnsysEDT 2023.

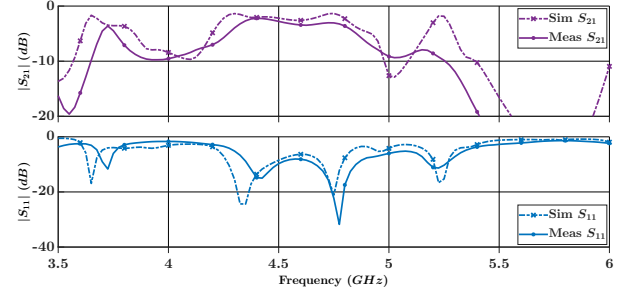


Fig. 4: Measurement and simulation results for the full fixture and no liquid coolant.

The full fixture is measured dry and with a liquid coolant that immerses the LUT and transitions. The results in Fig. 4 are without a liquid coolant (dry) and show a measured $|S_{11}|$ of $-15 dB$ and $|S_{21}|$ peak of $-2.2 dB$ at the design frequency of $4.4 GHz$. Fig. 5 shows the measurement results obtained when room-temperature EC-110 coolant from Engineered Fluids [10] is placed into the fixture and immerses the LUT for natural convection. The coolant is low-loss and has a dielectric constant of 2, therefore shifts in resonances are observed when compared to the results in Fig. 4, such that the transmission peak is now $-1.6 dB$ at $3.6 GHz$. Overall, there is reasonable agreement between the simulated and measured data for both cooling cases.

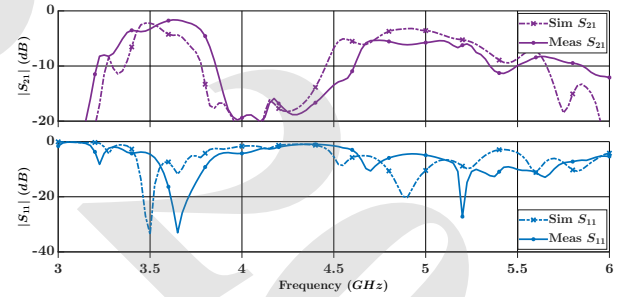


Fig. 5: Measurement and simulation results for the full fixture and EC-110 coolant.

Considering the inherently low losses in RWGs, a significant portion of the entire structure's loss is attributed to the through CPW. The LUT is a $94 mm$ long CPW line that connects the transitions, as shown in Fig. 3. This line separately introduces $0.6 - 1.3 dB$ of insertion loss over its length in the frequency range of $3-6 GHz$ when in air. Fixture losses here include the two coax-to-RWG adapters, the two RWG sections, and the two RWG-to-CPW transitions and backshorts. The commercial coax-to-RWG adapters have negligible loss, whereas the air-filled RWG sections of the fixture were found to contribute a combined maximum of $0.4 dB$ in insertion loss that arises due to the low-conductivity silver paint. The CPW transitions from

the air-filled RWGs are estimated to contribute $0.8 - 1$ dB to the total insertion loss at 4.4 GHz. However, this insertion loss is improved significantly with the liquid coolant, as it shifts the resonance frequency to 3.6 GHz where the transitions are well-matched. For the entire structure with the coolant, the measured return loss of over 30 dB at 3.6 GHz, and the corresponding insertion loss of 1.6 dB, confirm that minimal losses are introduced by the fixture.

B. External Temperature Measurements

Temperature measurements using an optical fiber temperature sensor on a CPW and a Luna ODiSI interrogator are shown here. Due to the low dielectric constant of the fiber sensor's jacket of approximately 2, its narrow diameter of 0.89 mm [11], and low thermal mass, this sensor enables temperature measurement without interfering with the electrical or thermal performance of the system. The optical sensors are therefore ideal for obtaining the temperature of planar microwave devices that are subjected to active cooling, and will be integrated directly in the test fixture.

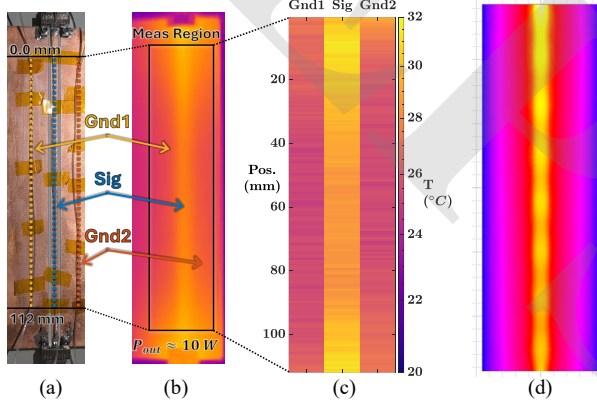


Fig. 6: (a) Temperature sensing optical fiber winding on CPW, (b) thermal camera steady-state reading, (c) thermal map from optical fiber sensor, and (d) simulated thermal map with the same scale as (c).

Fig. 6a is an image of a 140 mm long CPW with the optical fiber temperature sensors attached using Kapton tape. To verify the fiber measurements, a thermal camera is used to view the temperature at the CPW substrate. Good agreement is seen between the thermal camera view and the fiber measurements plotted as a colormap in Fig. 6b and Fig. 6c, respectively, as both figures show that the signal line has the highest temperature. This is confirmed by the simulated thermal map in Fig. 6d, where heat is seen to be generated mainly in and around the signal line and propagates to the rest of the structure. Additionally, the line is hottest at the input, before the signal undergoes any attenuation in the line.

For each fiber section in Fig. 6a, the maximum temperatures recorded against time are shown in Fig. 7. The temperature rises quickest in the first minute and begins to stabilize. Gnd1 is seen to have the lowest temperature because it is the widest section.

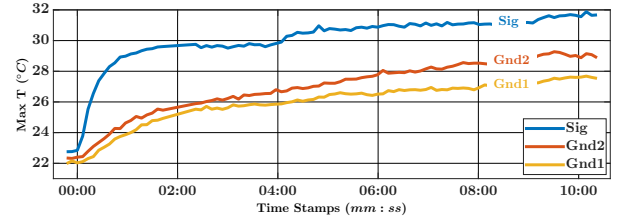


Fig. 7: Temperature profile for each fiber section on the CPW.

IV. CONCLUSION

This paper introduced a novel active-cooling test fixture for planar microwave networks. To validate this fixture, a through CPW was measured while submerged in a liquid coolant. Moreover, a non-intrusive temperature sensing approach that is compatible with the fixture is discussed and its measurement results are presented. Future work will investigate different cooling scenarios and simultaneous temperature measurements. The high transmission peaks and ease of scaling to other frequencies confirm that this design is viable for testing planar RF systems at high powers and with active cooling.

ACKNOWLEDGMENT

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