

# Pinhole-Enhanced Quarter-Wavelength Transmission Lines for Efficient Impedance Matching in Millimeter-Wave Circuits

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**Abstract**—This paper investigates the application of impedance matching using pinhole technology (PHT). By adjusting the ratio of air volume to substrate volume, the substrate's electrical properties, such as permittivity, are modified, resulting in a change in impedance. In this study, a simple microstrip line with a length of  $\lambda/4$  was designed at 3.6 GHz to match a load impedance of 80  $\Omega$  to 50  $\Omega$ . Subsequently, a microstrip line with a length of  $\lambda/4$  incorporating PHT was designed. Simulation results validate the effectiveness of the proposed design process, demonstrating close agreement with the theoretical performance of impedance-matching lines. The PHT line's smoother and more gradual transition suggests that the pinhole structure helps dampen reflections, improving matching performance.

## I. INTRODUCTION

Impedance matching is fundamental in microwave engineering, ensuring maximum power transfer between circuit elements while minimizing reflections [1]. One widely used method for impedance matching is the use of a quarter-wavelength ( $\lambda/4$ ) transmission line, which transforms the impedance of a load to match the characteristic impedance of the source [1]. The  $\lambda/4$  line technique relies on the property that the impedance transformation relationship determines the input impedance of a transmission line at a specific frequency. This makes the method particularly effective for narrowband applications, such as antenna matching and RF circuit design [1]. By carefully selecting the length and characteristic impedance of the  $\lambda/4$  line, engineers can efficiently match loads with different impedance values to achieve the desired performance [2] [3] [4].

In this paper, we investigate the design and simulation of a simple microstrip line with a length of  $\lambda/4$  at 3.6 GHz on a substrate with permittivity 2.8, aimed at matching a load impedance of 80  $\Omega$  to 50  $\Omega$ . Additionally, we explored the incorporation of PHT into the  $\lambda/4$  line to assess its impact on impedance-matching performance. Also, we used this technique to match a load impedance of 80  $\Omega$  to 50  $\Omega$  to compare the results (Figure 1).

## II. EXTRACTION TECHNIQUE AND RESULTS

Traditional small signal parameters like Z, Y, and ABCD are unsuitable for high-frequency interconnect characterizations because the realization of the required OPEN and SHORT

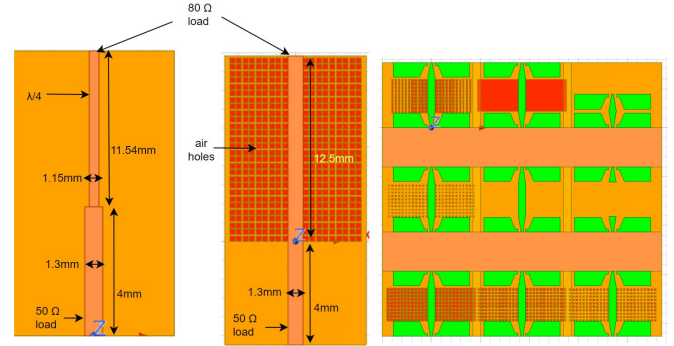


Fig. 1. Schematic of impedance matching with simple  $\lambda/4$  line,  $\lambda/4$  line with PHT and Reticle of holes with different size.

circuit terminations is challenging. "SHORT" circuit terminations exhibit magnetically induced inductance, while "OPEN" circuit terminations entail additional capacitance to capture fringing electric fields at high frequencies. Conversely, S parameters, defined in terms of incident and reflected waves within a controlled 50-ohm measurement system, effectively characterize the high-frequency response of interconnects [5]. In this study, we initially utilized a microstrip line as the guiding structure to determine permittivity and line impedance by obtaining S parameters, which are then converted into an ABCD matrix.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (1)$$

For a transmission line of length L with characteristic impedance  $Z_c$ , the ABCD parameters are linked to the line dimensions and its complex propagation constant, where  $\gamma = \alpha + j\beta$ . In this context,  $\alpha$  and  $\beta$  denote the attenuation and phase constant of the transmission line, respectively. The relevant equations are listed as follows [6] [4].

$$\begin{aligned} A &= \cosh \gamma L & B &= Z_c \sinh \gamma L \\ C &= \frac{\sinh \gamma L}{Z_c} & D &= \cosh \gamma L \end{aligned} \quad (2)$$

By combining the above equations, the line attenuation  $\alpha$  and phase constant  $\beta$  can be derived. The units for  $\gamma$  and  $\beta$  are dB/m and rad/m, respectively [6] [4]. As shown in

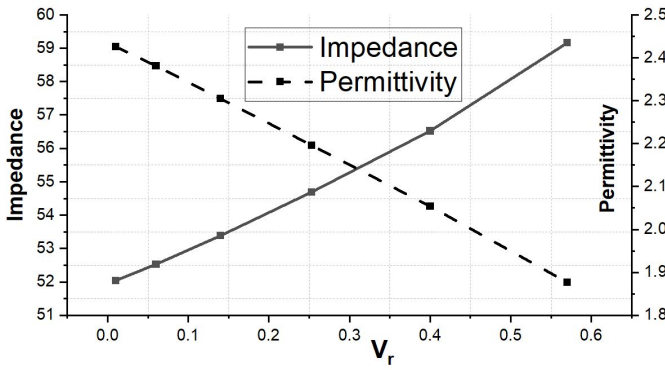


Fig. 2. Permittivity and Impedance versus filling ratio for a transmission line implemented with PHT.

Figure 1, we designed and fabricated a reticle using a dielectric material substrate, incorporating holes of varying sizes and spacing to validate the proposed method. A ground-signal-ground (GSG) probe was employed for testing, and through-reflect-line (TRL) calibration was performed to accurately de-embed the  $S$ -parameter data. [7] [8] [2] Figure 1 illustrates the simulation results for the reticle, demonstrating the impact of PTH on the impedance and permittivity of the line, where  $V_r$  represents the volumetric ratio of air to substrate. Based on the results shown in Figure 2, we designed a  $\lambda/4$  line for impedance matching, as illustrated in Figure 1. Figure 3 presents the  $S$ -parameter results, which closely align with the expected values. The graphs for both methods demonstrate strong agreement. Additionally, to validate these results, a time-domain reflectometry (TDR) graph for both methods is shown in Figure 4, illustrating consistent outcomes across both approaches. A comparison of the results of the TDR plot shows that the simple line (solid line) maintains a higher impedance throughout the transition, while the PHT line (dashed line) exhibits consistently lower impedance, particularly during the transition phase. The simple line transitions more steeply between  $50\ \Omega$  and  $90\ \Omega$ . In contrast, the PHT line demonstrates a smoother and more gradual transition, indicating the potential impact of the pinhole structure in dampening reflections. This smoother transition likely enhances overall matching performance and reduces reflections in practical applications. Although the simple line stabilizes faster, it may exhibit sharper reflections, making it more sensitive to impedance mismatches.

### III. CONCLUSION

This paper introduces a novel impedance matching approach using pinhole technology (PHT) integrated with a  $\lambda/4$  transmission line. By adjusting the air-to-substrate volumetric ratio ( $V_r$ ), PHT effectively modifies substrate properties, enabling precise impedance control. Simulation results validated the proposed method, showing strong agreement with theoretical predictions. Performance analysis using  $S$ -parameters and TDR confirmed the effectiveness of PHT, demonstrating smoother transitions and reduced reflections

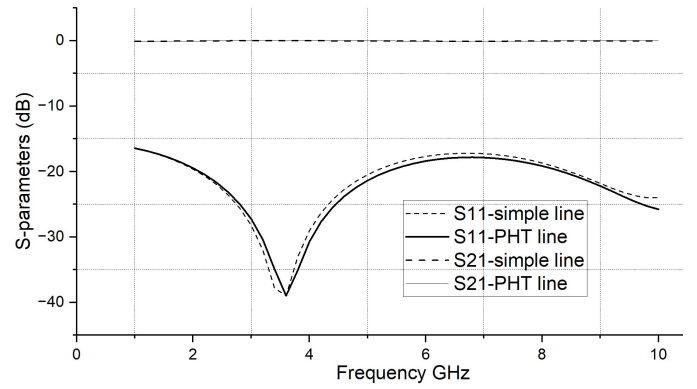


Fig. 3.  $S$ -parameters results for simple impedance matching circuit and PHT.

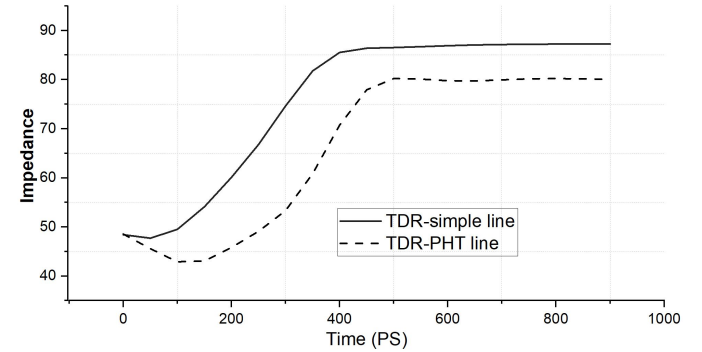


Fig. 4. TDR for simple impedance matching circuit and PHT

compared to conventional designs. PHT shows great potential for achieving efficient and reliable impedance matching in microwave and millimeter-wave applications. Future work could explore extending this approach to broader frequency ranges and applying it to more complex RF systems, such as antenna arrays and filters.

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