Rectangular to Parallel Plate Waveguide Transition and Its Tapering Effect for Microwave Devices Characterization

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Abstract: The experimental characterization in exploiting the property of microwave devices is an essential complement to theoretical and/or simulation works. Thus, the need of instrument for the characterization is becoming unavoidable thing to be established. This paper reports the development of test-fixture in form of a parallel plate waveguide (PPW) to characterize the reflectivity and/or transmittivity of microwave device whereby the property of reflection and/or transmission can be achieved under normal incidence. Since the PPW is excited using a rectangular waveguide, a transition section which connects the rectangular waveguide and the PPW needs to be investigated to have an optimum performance required for microwave devices characterization. The tapering effect of transition section is examined and analyzed numerically in yielding the influences to the test-fixture performance. Here, a WR248 type rectangular waveguide which has working frequency of 2.60GHz to 3.95GHz for TE_{10} mode is used as coaxial-to-waveguide transducer for exciting the PPW. The result shows that the linear-tapered transition has better performance in term of bandwidth compared to the step-tapered one. In addition, the discussions of taper length and number of step-tapered transition related to the performance of test-fixture as well as the experimental characterization for linear-tapered transition are also presented.

Keywords: coax-to-waveguide transducer, linear-tapered transition section, microwave devices, parallel plate waveguide, rectangular waveguide, step-tapered transition section.

1. Introduction

One of the important things in the design of microwave devices is the experimental characterization to compare and verify the characteristic of realized devices to comply with the design or specification. Unfortunately, for some devices with infinite number of structures or unit cell such as frequency selective surfaces (FSS), there is often impossible to directly measure their characteristics, i.e. reflectivity or transmittivity, especially at microwave frequency or the higher one. Some methods by using close-sided waveguide simulators have been applied to obtain the properties of array elements and FSS [1]-[4]. However, due to the nature of these simulators they suffer from the problem that the device under test (DUT) could be characterized only for certain angle of incidence which is positioned away from the path of normal incidence. To cope with this problem, a parallel plate waveguide (PPW) method was implemented as an alternative technique [5]-[6]. By using this method, the characterization of infinite number of structures can be carried out using a finite one since the walls of PPW behave as pairs of image planes.

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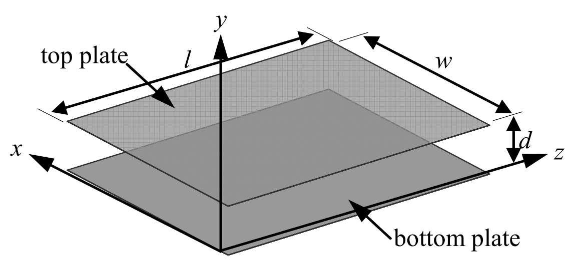
Based upon the application of finite element modeling technique, the concept of PPW has been applied in many microwave measurements [5]-[7]. Instead of only as an experimental test-fixture such as for measuring the reflectivity and/or transmittivity, the PPW method is sometimes used as a theoretical means of evaluating the characteristics of several structures or devices. Since the method has the capability to make an enclosed structure which appears as an infinitely periodic environment [8], therefore it has possibility to be implemented for performing laboratory measurement under controlled conditions. In principle, to be able for experimental characterization, the PPW is usually is illuminated by using a specific mode of plane wave which is excited from a wave exciter. The coaxial-to-waveguide transducer is commonly used as a wave exciter due to the advantage in ease of construction and excess of performance [5], [7]. Whilst in [6], for simplifying the high frequency measurement the PPW applies coaxial wave excitation as a complement of coaxial-to-waveguide transducer.

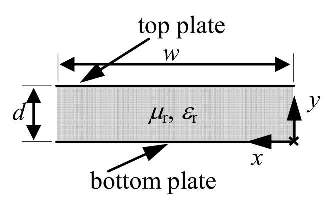
In order to have an optimum performance of PPW-based test-fixture, in place of directly connecting the rectangular waveguide that acts as a wave exciter to the PPW [5], a transition section between the waveguide and the PPW is required to minimize the reflection loss which occurs due to the impedance mismatch of both. The similar section referred as converter has also been used to connect a circular waveguide and a coaxial-to-waveguide transducer in form of rectangular shape to overcome the problem of circular waveguide excitation [9]-[10]. Therefore, in this paper the investigation of rectangular to PPW transition is carried out by examining and analyzing the tapering effect of transition section to the performance of test-fixture. The paper is organized as follows: at first the basic theory related to the PPW as a major element of test-fixture will be explained briefly. The cut-off frequency, resonance modes, and wave impedance of PPW are also included in the explanation. Then, the investigation of tapering effect of transition section as well as the taper length and the number of step-tapered transition section to PPW parameter is carried out numerically and followed by characterization for realized test-fixture. The discussion related to the numerical investigation and the experimental characterization will be presented consecutively and followed by the conclusion.

2. Brief Review of Parallel Plate Waveguide and Tapered Transition

A. Properties of Parallel Plate Waveguide



(a) rough view



(b) front view

Figure 1. Illustration of parallel plate waveguide

The simplest guide wave structure which is frequently used for the transmission line is the PPW. As illustrated in Figure 1, the PPW structure is constructed of two parallel metal plates which are separated by distance *d*. The plate width *w* and the plate length *l* are assumed to be much greater than *d*. In this case, no medium fills the area between the plates other than free space ($\mu_r = \varepsilon_r = 1$). The electric and magnetic fields associated with electromagnetic waves that propagate between the plates satisfy source-free Maxwell's equations. As for the case of transmission line, the effect of losses coming from medium and plates is initially neglected. The types of waves that can be supported in an empty loss-free PPW are the Transverse

Electric (TE) wave mode with no electric field component in the propagation direction ($E_z = 0$, $H_z \neq 0$), and the Transverse Magnetic (TM) wave mode with no magnetic field component in the propagation direction ($E_z \neq 0$, $H_z = 0$). It should be noted that the electric and magnetic fields are assumed to propagate in *z* direction.

Since the structure is a loss-free PPW, thence it has only imaginary part of propagation constant ($\alpha = 0$, $\gamma = j\beta$). This condition allows the wave modes to propagate in the PPW where it operates at frequency higher than its cut-off frequency. The cut-off frequency for TE and TM wave modes is given by (1) [8], [11].

$$f_{c,m}^{TE} = f_{c,m}^{TM} = \frac{c \cdot m}{2d\sqrt{\mu_r \varepsilon_r}} \tag{1}$$

where *c* is the light velocity at free space (3 x 10^8 ms^{-1}), and *m* is an integer (1,2,3,…) which is related to the number of field variations in *y*-direction. Figure 2 plots the cut-off frequency of TE and TM wave modes for the first three values of *m* in which the distance *d* is varied from 50mm to 100mm. From the figure, it notes that the lowest wave mode is the TE_1 or TM_1 wave mode, and is normally the one used.

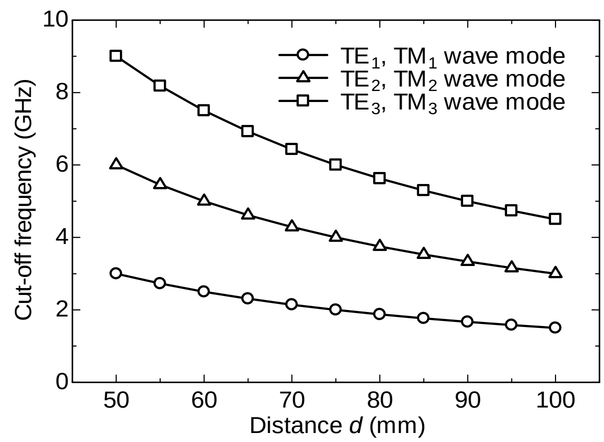


Figure 2. Cut-off frequency of TE and TM wave modes for first three values of *m*

In contrast to both cut-off frequencies which are similar each other, wave impedances for the TE_1 and TM_1 wave modes are oppositely each other where they are expressed in (2) and (3) for the TE_1 and TM_1 wave modes, respectively.

$$Z_{TE1} = \frac{k_0}{\sqrt{k_0^2 - (\pi/d)^2}} Z_0 \tag{2}$$

$$Z_{TM1} = \frac{\sqrt{k_0^2 - (\pi/d)^2}}{k_0} Z_0 \tag{3}$$

where k_0 is wavenumber which is defined as $k_0 = \omega\sqrt{\mu_0 \varepsilon_0}$ and Z_0 is the characteristic impedance of free space, i.e. 120π Ω. Figure 3 depicts the theoretical wave impedance for the TE_1 and TM_1 wave modes with the distance *d* of 75mm. It shows that for higher frequencies, the wave impedances for both wave modes are converged approaching the characteristic impedance of free space.

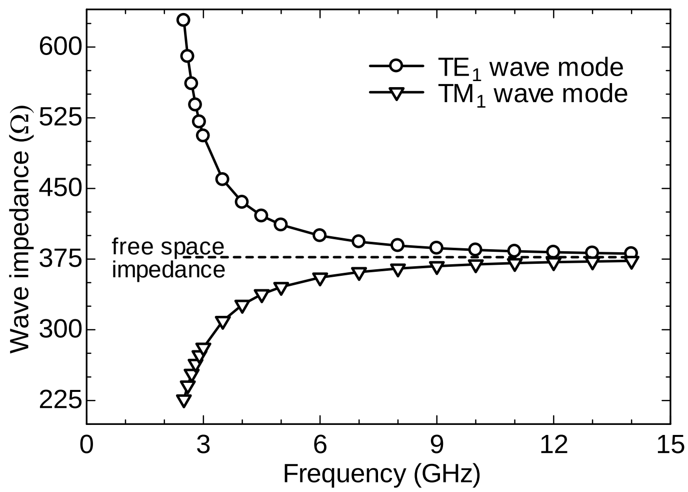


Figure 3. Wave impedances for TE_1 and TM_1 wave modes with distance d of 75mm

B. Analysis of Tapered Transition

In practical implementation, the PPW is usually illuminated using waveguide as a wave exciter. The used waveguide which is usually a rectangular type can be connected to the PPW either directly or through a transition section. In case of the rectangular waveguide dimension, i.e. the height, is different with the PPW dimension, i.e. the distance between plates, the transition section is mostly required for adapting both dimensions. In addition, the transition section is also applicable for improving impedance matching between the PPW and the rectangular waveguide. Some type of transition section frequently used is tapered one as shown in Figure 4.

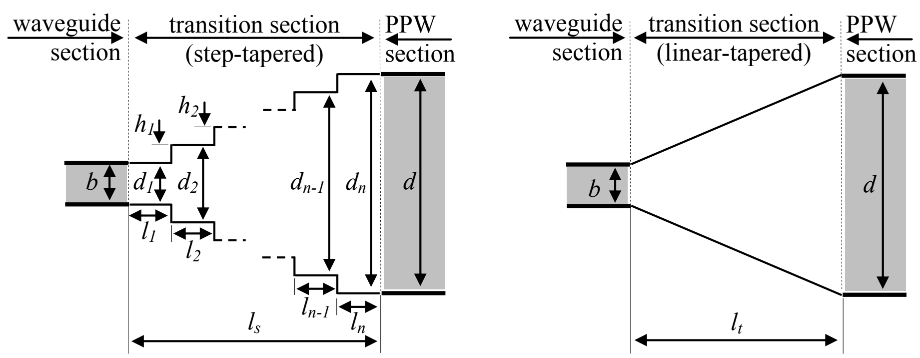


Figure 4. Side view of PPW connected with rectangular waveguide using tapered transition section

By considering b is the height of rectangular waveguide, e.g. coaxial-to-waveguide transducer and d is the distance between two plates of PPW, then both are connected using a step-tapered transition section with the length of l_s as shown in Figure 4(a). The transition section is divided uniformly into n steps, so that the length (l_n) and the height (h_n) of each step are uniform and can be expressed in (4) and (5), respectively.

$$l_1 = \dots = l_n = \frac{l_s}{n-1} \tag{4}$$

$$h_1 = \ldots = h_n = \frac{d - b}{2(n-1)} \tag{5}$$

The distance between plates (d_i) of i-th step, i.e. i = 1, 2, 3,..., n-1, can be calculated using (6). Since for each step the distance d has a specific value, this affects to wave impedances. Thus for the TE_1 and TM_1 wave modes, (2) and (3) should be redefined as written in (7) and (8), respectively.

$$d_i = b + 2(i-1)h \tag{6}$$

$$Z_{TE1-i} = \frac{k_0}{\sqrt{k_0^2 - (\pi/d_i)^2}} Z_0 \tag{7}$$

$$Z_{TM1-i} = \frac{\sqrt{k_0^2 - (\pi/d_i)^2}}{k_0} Z_0 \tag{8}$$

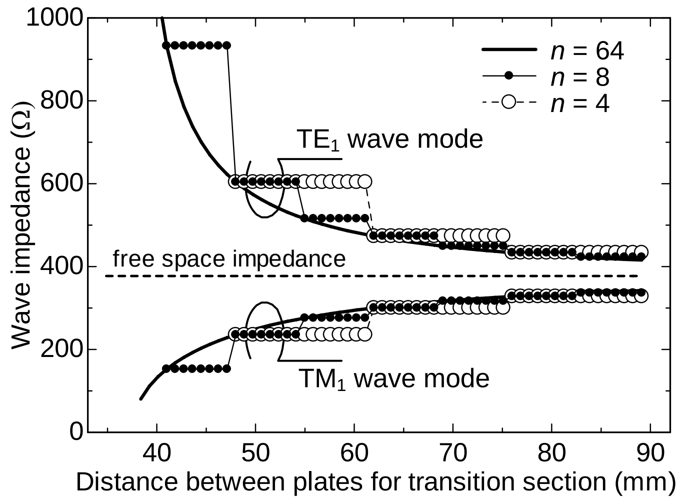


Figure 5. Wave impedances of step-tapered transition section at frequency of 4GHz for TE_1 and TM_1 wave modes

Figure 5 plots wave impedances of step-tapered transition section calculated using (7) and (8) at frequency of 4GHz for the TE_1 and TM_1 wave modes. The transition section which has the length l_s of 100mm is divided uniformly into three n steps, i.e. 4 steps, 8 steps, 64 steps, to connect a rectangular waveguide with the height b of 34mm and a PPW with the distance d of 90mm. It is seen that the wave impedances of i-th step are gradually changed following the value of d. The larger number of step n the smoother wave impedance obtained. This is usefulness of transition section for minimizing the impedance mismatch between rectangular waveguide and PPW in addition to the geometry matching between both dimensions. In contrary, the geometry of linear-tapered transition section as shown in Figure 4(b) is simpler than the step-tapered transition section. The important parameters in designing the linear-tapered transition section are the length (l_t), the distance between plate (d), and the height of rectangular waveguide (b). Actually the linear-tapered transition section is a special geometry condition of step-tapered transition section, in which the number of step n is large enough affecting to the much smaller value of the length (l_n) and the height (h_n) of each step. This is shown in Figure 5 for number of step n of 64. Therefore, the wave impedances of the linier-tapered transition are smoother than of the step-tapered one.

3. Characterization and Discussion

A. Numerical Characterization

A rough sketch of test-fixture for numerical characterization is illustrated in Figure. 6. It comprises of a rectangular waveguide and a PPW in which both are connected using transition section. The rectangular waveguide of WR248 type with the width *a* of 72mm and the height *b* of 34mm which has working frequency of 2.60GHz to 3.95GHz for TE_{10} wave mode is used as coaxial-to-waveguide transducer for exciting the PPW. Meanwhile, the PPW has the length *l* of 600mm, distance *d* of 90mm and the width *w* of 200mm. In the investigation, 2 types of transition section, i.e. step-tapered and linear-tapered transition sections, are applied for the characterization to obtain the optimum performance in term of reflection coefficient, impedance and working bandwidth. At first, both transition sections are set to have 100mm length. The number of step *n* for step-tapered transition section is varied from 4 to 16 steps where the length and the height of each step are identical each other.

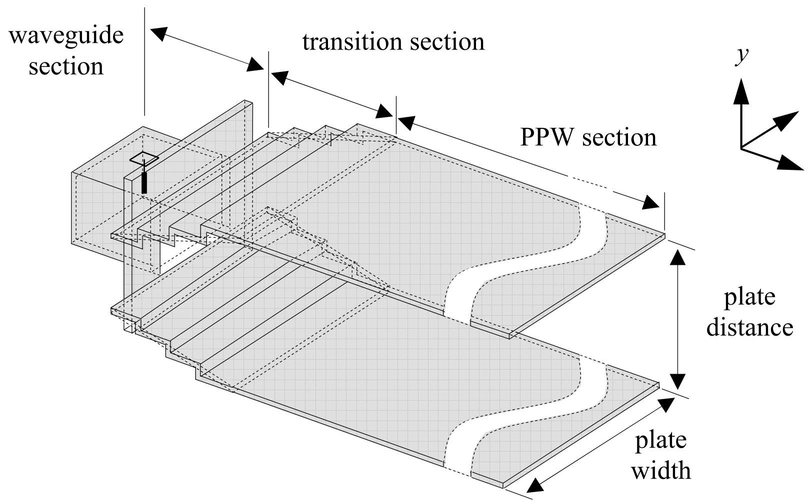


Figure 6. Rough sketch of test-fixture for numerical characterization

As plotted in Figure 7, the reflection coefficient of test-fixture which uses step-tapered transition section for small number of step, i.e. 4 steps and 8 steps, is higher than the large number of step. This is addressed to the higher impedance mismatch for small number of step; as a result more reflected waves occur. The result complies with the theoretical prediction in previous section that the smaller number of step produces the larger different of impedance in each step. From the result it seems that the linear-tapered transition section gives smaller fluctuation of reflection coefficient compared to the step-tapered transition section for frequency range of 2.6GHz to 3.5GHz. This will be beneficial for stability measurement in characterizing microwave devices. Furthermore, the impedance in inside of test-fixture at frequency of 3GHz and the working bandwidth are depicted in Figures 8 and 9, respectively. It could be noted that the 4 steps used in step-tapered transition section has larger fluctuation of impedance than others. The fluctuation is reduced when the larger number of step, i.e. 8 steps or 16 steps, or a linear-tapered transition is employed. In despite of having fluctuated impedance, its working bandwidth is the widest one, i.e. around 2.15GHz, as shown in Figure 9. Here, the working bandwidth is defined as the band of frequency bounded by reflection coefficient of -10dB. As the 4 steps of step-tapered transition section has the lowest transmitted power compared with others indicated by the worst reflection coefficient, due to a trade-off between the transmitted power and the bandwidth, therefore the widest working bandwidth is obtained.

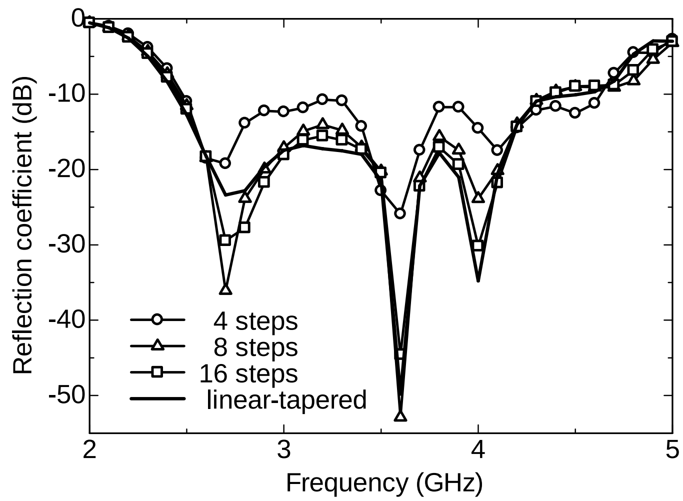


Figure 7. Reflection coefficient of test-fixture using step-tapered and linear-tapered transition sections

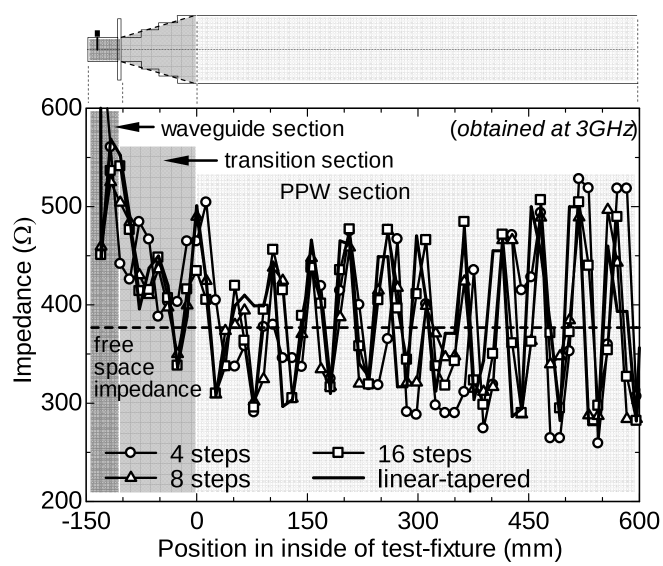


Figure 8. Impedance in inside of test-fixture using step-tapered and linear-tapered transition sections

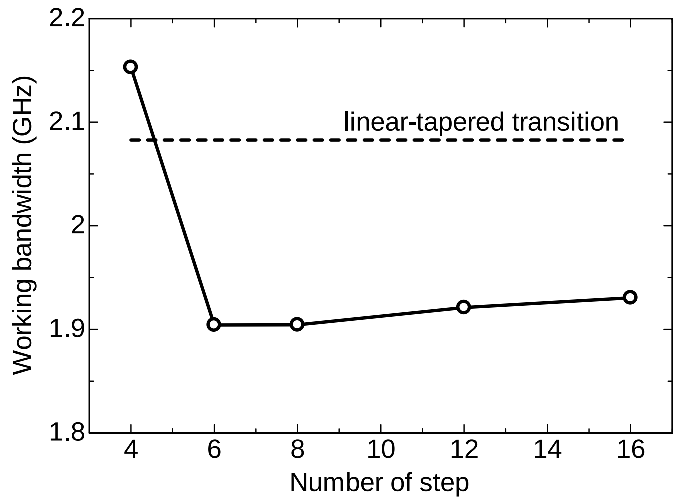


Figure 9. Working bandwidth of test-fixture using step-tapered and linear-tapered transition sections

As the next investigation, the length of transition section for step-tapered transition is varied from 50mm to 150mm where the number of step 4 is applied for numerical characterization. Figures 10 and 11 plot the reflection coefficient and the impedance for test-fixture at frequency of 3GHz which uses step-tapered transition section, respectively. It shows that the length of transition section of 75mm produces the better reflection coefficient compared to other lengths for frequency range of 2.6GHz to 3.0GHz. The length of 75mm has also the smallest fluctuation of impedance as plotted in Figure 11. However, for higher frequency range, i.e. 3.0GHz to 3.4GHz, the length of 50mm seems to be better than others in term of reflection coefficient. Therefore, this will be an advantage for improving the accuracy of microwave devices characterization which has frequency response belong that frequency range.

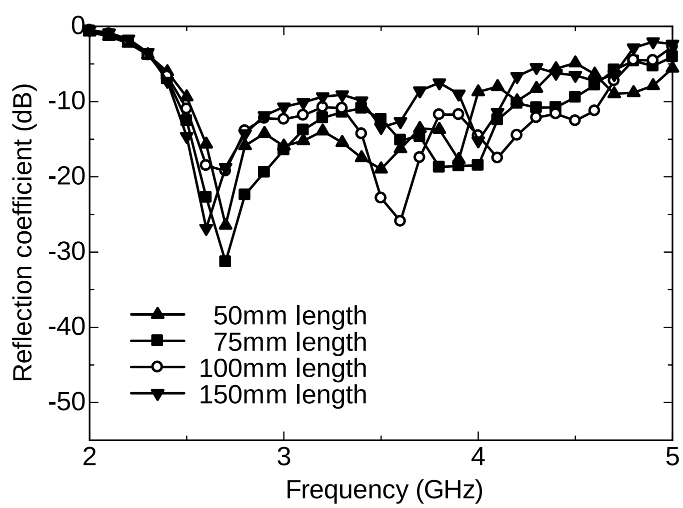


Figure 10. Reflection coefficient of test-fixture using step-tapered transition section of 4 steps with different length of transition section

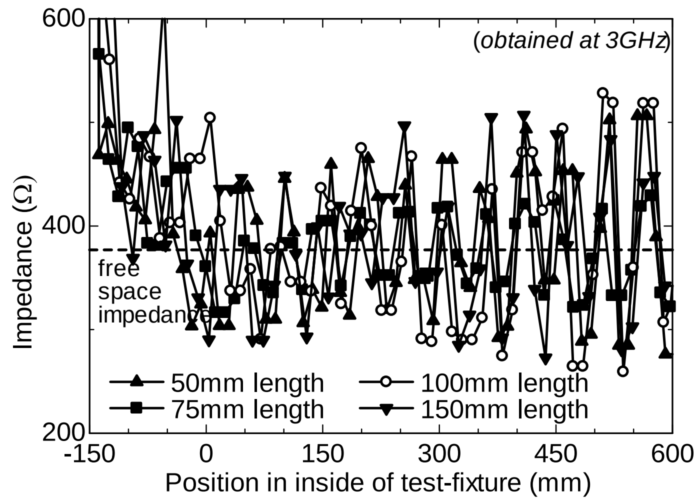


Figure 11. Impedance in inside of test-fixture using step-tapered transition section of 4 steps with different length of transition section

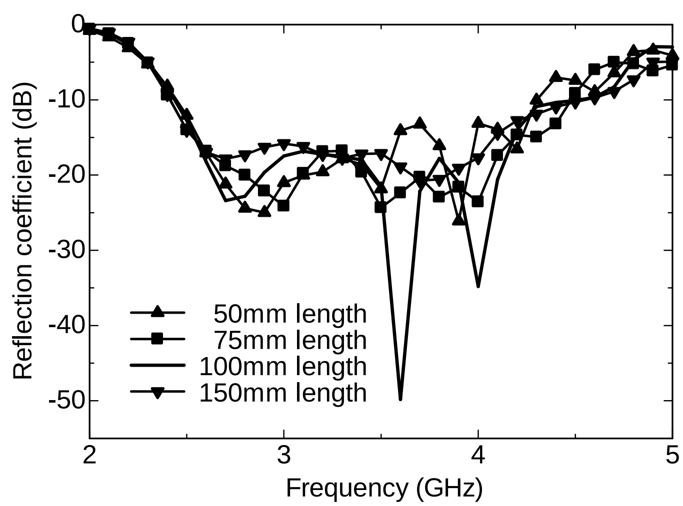


Figure 12. Reflection coefficient of test-fixture using linear-tapered transition section with different length of transition section

In comparison to the step-tapered transition, the investigation for length variation of linear-tapered transition section to the performance of test-fixture is examined. As the previous investigation, the length of linear-tapered transition is varied from 50mm to 150mm. The results are depicted in Figures 12 and 13 for the reflection coefficient and the impedance in inside of test-fixture at frequency of 3GHz, respectively. It can be noted from Figure 12 that the length of linear-tapered transition section of 75mm yields the reflection coefficient which is better than other lengths for frequency range of 2.6GHz to 3.0GHz. It can also be seen in the impedance plotted in Figure 13 where the length of linear-tapered transition section of 75mm has smallest fluctuation. This is similar as the previous investigation of using step-tapered transition section of 4 steps. However, for frequency range from 3.0GHz to 3.4GHz, although the impedance has more fluctuated values, the length of 50mm shows better performance compared to others where this also coincides with the step-tapered transition section of 4 steps.

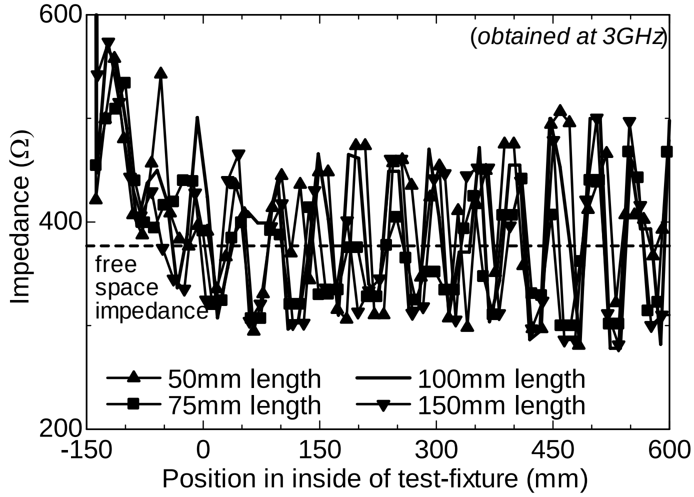


Figure 13. Impedance in inside of test-fixture using linear-tapered transition section with different length of transition section

Hence, it can be inferred that the test-fixture with length of transition sections of 75mm is suitable to be applied for characterizing microwave devices which has working frequency below 3GHz. Meanwhile, for the devices with higher frequency response, it can be characterized using test-fixture with a shorter length of transition section. Furthermore, as shown in Figure 14, the working bandwidth of test-fixture using linear-tapered transition for varied length of transition section is flatter than of the step-tapered transition section. The results indicate that the varied length of linear-tapered transition section gives no significant influence for working bandwidth response compared to the step-tapered transition. The widest working bandwidth is obtained by the test-fixture using linear-tapered transition section with the length of 150mm, i.e. 2.136GHz, whereas from the step-tapered transition of 4 steps, the widest one is 2.153GHz which is produced by the length of 100mm.

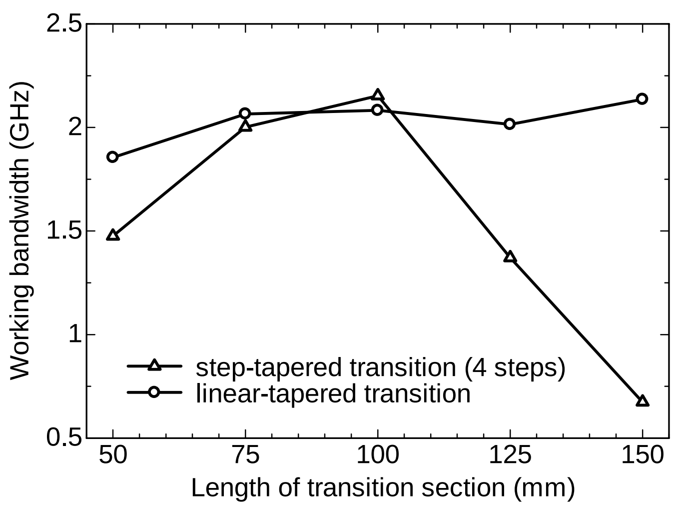
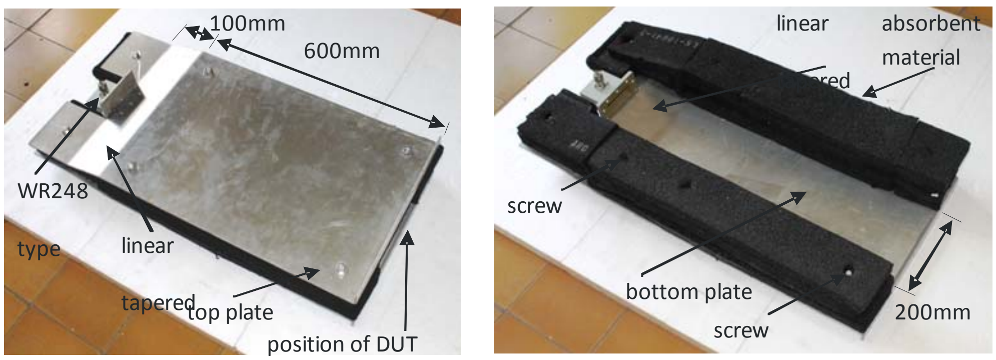


Figure 14. Working bandwidth comparison of test-fixture with varied length of transition section for step-tapered transition section of 4 steps and linear-tapered transition section

B. Realization and Experimental Characterization

Based on the numerical characterization, by considering the ease of fabrication, a test-fixture with linear-tapered transition section of 100mm length is realized for experimental characterization. In addition, from the numerical result it has been shown that the linear-tapered transition section of 100 length has wide enough of working bandwidth and small enough of impedance fluctuation. As shown in Figure. 15, the test-fixture is fabricated using a 2mm aluminum sheet for top and bottom plates as well as for linear-tapered transition section. Where as a WR248 type rectangular waveguide as coaxial-to-waveguide transducer for exciting the PPW is installed separately. The absorbent materials are placed surrounding the test-fixture at the outside of 200mm plate width as shown in Figure. 15(b) to avoid interferences coming from the front end test-fixture to the outside or vice versa. In addition, 4 pairs of non-metallic screw are employed at the area of absorbent material to keep the distance between plates of 90mm. In practical, the DUT of microwave devices such as FSS are positioned at the front-end of PPW away from the waveguide rectangular.



(a) overall view of test-fixture (b) test-fixture without top plate

Figure 15. Picture of fabricated test-fixture with linear-tapered transition section

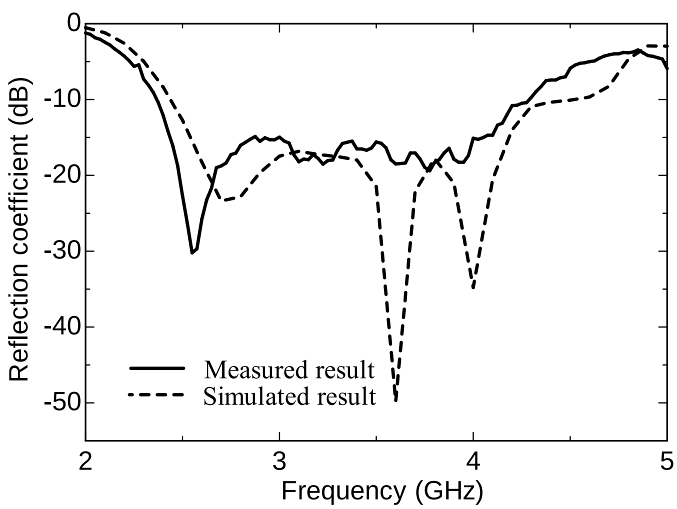


Figure 16. Measured reflection coefficient of test-fixture with linear-tapered transition section with numerical result as comparison

The experimental characterization result of fabricated test-fixture is depicted in Figure 16 where the numerical result is plotted together as comparison. Some discrepancies appear at frequency range of 2.65GHz to 3GHz and 3.3GHz to 3.75GHz, where the measured reflection coefficient is higher than simulated one with the maximum different value about 30dB which happened at frequency of 3.6GHz. The differences are also seen in higher frequency range of 3.8GHz to 4.8GHz with the maximum value of 20dB at frequency of 4GHz. These happened as there were some different conditions and assumptions, such as the used material parameters and boundary conditions. It should be noted that the parameters of material and the boundary condition applied in the numerical characterization are frequency independent and perfectly absorbing material, respectively. Nevertheless, from the experimental characterization, it can be concluded that the characteristic of realized test-fixture with linear-tapered transition section of 100mm length has coincided qualitatively with the numerical one; therefore, it is suitable for microwave device characterization.

4. Conclusion

The tapering effect of transition section for connecting a rectangular waveguide and a parallel plate waveguide (PPW) has been investigated related to the design of test-fixture for microwave devices characterization. In addition to matching the different geometry between the rectangular waveguide and the PPW, it has been shown that the transition section both in form of step-tapered and linear-tapered transition sections can minimize the impedance mismatch between the rectangular waveguide and the PPW. It has been demonstrated that the higher number of step for test-fixture with step-tapered transition section has minimized the reflection coefficient and increased the stability of impedance in inside of test-fixture. Meanwhile, the length of transition section for test-fixture with linear-tapered transition section has had no significant effect to the working bandwidth achievement where it was contradictive with step-tapered transition of 4 steps. In addition, in despite of discrepancy in the measured result, in general the experimental characterization of realized test-fixture with linear-tapered transition section has shown a good agreement with the numerical one. This will be beneficial in the development of other instruments for microwave device characterization.

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