Rectangular to Circular Waveguide Converter for Microwave Devices Characterization

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Abstract: In this paper, a rectangular to circular waveguide converter is investigated numerically and characterized experimentally for microwave devices characterization. The converter is designed as an excitation method of circular waveguide to produce its dominant mode as the problem of circular waveguide in the excitation process. A WR248 type rectangular waveguide transducer with working frequency of 2.60–3.95GHz for TE_{10} mode is used as the wave exciter to be converted to a WC248 type circular waveguide. Prior to the fabrication, physical parameters of converter including length of rectangular segment, length of transition segment and length of circular segment are analyzed to obtain the optimum design. It shows that the length of transition segment affects to the return loss of converter and its length to produce TE_{11} mode of circular waveguide smoothly has to be more than twice of waveguide wavelength. From the result, the length of transition segment is chosen to be 275mm as it demonstrates better return loss compared to other lengths almost in the designated working frequency. To verify the design result, the prototype of converter is then realized and characterized experimentally. Furthermore, some discussion related to the results of experimental characterization is also presented.

Keywords: circular waveguide, dominant mode, excitation, rectangular waveguide, waveguide converter.

1. Introduction

It is well known that the main problem in transmission of electromagnetic energy in some media is the effectiveness and the optimality of delivery. This also applies to waveguides since the delivery of electromagnetic energy is often ineffective interfered by the presence of attenuations especially in microwave frequencies. Attenuations in the waveguide commonly come from dielectric and conductor losses. Therefore, the used dielectric inside waveguide usually is air which has lower loss than other insulation types, whilst the loss coming from conductor wall is sometime suppressed by use of a metal with high conductivity [1]-[2]. Beside the attenuation problem another issue that has to be paid more attention is the excitation method especially for some waveguide applied as a transmission line [3]-[4]. Basically, there are various types of waveguide based on the physical shape, such as rectangular, circular, truncated, and elliptical. The circular type is a special case of elliptical waveguide type which has the lowest attenuation and the capability to generate dual polarization. However, its excitation method is to be the main issue that hampers in practical application. This problem occurs as the dominant mode of circular waveguide is not as simple as the dominant mode of other type such as rectangular waveguide. In contrary, the rectangular waveguide which has a relatively higher attenuation compared with other types of waveguide is frequently used due to the ease of excitation method that can be made by using a monopole antenna or current loops as a probe [5]-[6].

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To maximize the advantage of rectangular waveguide and minimize the disadvantage of circular waveguide, in this paper an instrument that has an ability to convert the excitation process from rectangular to circular waveguide is proposed to be designed for microwave devices characterization. This instrument is expected as a solution to provide the parameters of transmission efficiency, large dimension, polarization, and ease of excitation method in waveguide as a transmission line [7]-[8]. The instrument called as rectangular to circular waveguide converter is then able to be used, for example, to help analyze and characterize the property of circular type of material especially in microwave region. The converter is excited from a WR248 type rectangular waveguide transducer to produce a dominant mode of WC248 type circular waveguide. In the design, the frequency range for investigation is limited by the transducer which has working frequency of 2.60–3.95GHz. Prior to the fabrication, some physical parameters of converter such as the length of rectangular segment, the length of transition segment and the length of circular segment are analyzed numerically based on the return loss performance that uses as the design criteria.

The paper is organized as follows: at first the basic theory related to rectangular waveguide, circular waveguide and the converter will be described briefly prior to the design process. The modes of both waveguides are also included in the description. Then, the design and its analysis of converter are carried out based on the specification and design criteria. Some optimization process is applied to the physical parameters of converter including the length of rectangular segment, the length of transition segment and the length of circular segment to obtain the optimum design. From the design result, the prototype of converter is then realized to be characterized experimentally. Here, the discussion related to the result of experimental characterization in comparison with the design result will be presented consecutively and then followed by the conclusion.

2. Basic Theory

A. Rectangular and Circular Waveguides

A waveguide, based on its shape is divided into several types, namely rectangular, circular, elliptical, and truncated waveguide. In this paper, the discussion is limited to the rectangular and the circular waveguides for the investigation purposes. Each mode in those waveguides has a cut off frequency (f_c) with a certain value. At the working frequency (f), only the mode which has $f > f_c$ would propagate, whilst the modes with $f < f_c$ would produce imaginary electromagnetic field components and have no propagation. If the waveguide produces more propagation modes, then the waveguide will be over mode. The lowest mode excited in the waveguide is called a dominant mode. For rectangular waveguide as illustrated in Figure 1, the cut off frequency can be formulated as follows [2]-[3].

$$f_{c,mn} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}, \tag{1}$$

where a, b, μ, and ε are the width of waveguide, the height of waveguide, the permeability of material inside of waveguide, and the permittivity of material inside of waveguide, respectively. Hence, m and n that are integers (0, 1, 2, …) denote the number of waveguide mode that corresponding to the dimension of a and b. By assuming that $a > b$, then the dominant mode occurs at TE_{10} (transverse electric) mode in which the cut-off frequency (f_c) for $m = 1$ and $n = 0$ can be derived from (1) and is expressed as follows [2]-[3].

$$f_{c,10} = \frac{1}{2a\sqrt{\mu\varepsilon}} \tag{2}$$

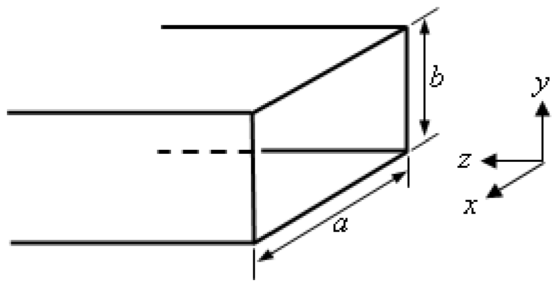

Figure 1. Illustration of rectangular waveguide

Due to the finite conductivity of waveguide inside walls, the attenuation decreases along the increase of frequency at $f > f_c$ up to a minimum value and increases again for given b/a ratio [2]. For a rectangular waveguide with the ratio of $b/a < 0.5$, the successive higher-order modes are TE_{20}, TE_{01}, TE_{11}, etc. Therefore, the dimensions of the cross section which ensure only the dominant mode propagation are determined as follows [6].

$$\begin{aligned} \lambda_{\max} &< \lambda_c, \mathrm{TE}_{10} = 2a \\ \lambda_{\min} &< \lambda_c, \mathrm{TE}_{20} = a \\ \lambda_{\min} &< \lambda_c, \mathrm{TE}_{01} = 2b \end{aligned} \tag{3}$$

A rectangular waveguide is frequently found in numerous applications as it has several advantages such as easy excitation, feeder generally made for rectangular (connection to another waveguide easier to install), and relatively easy calculation and design. Unfortunately, this type has quite higher attenuation than other type of waveguide. This occurs because of the dielectric loss inside the waveguide and conductor loss inside wall. In addition, the rectangular waveguide cannot produce TM_{00} (transverse magnetic), TM_{01}, and TM_{10} and have no dual mode polarization. The electromagnetic field distribution across front section of rectangular waveguide at TE_{10} dominant mode is shown in Figure 2 [3].

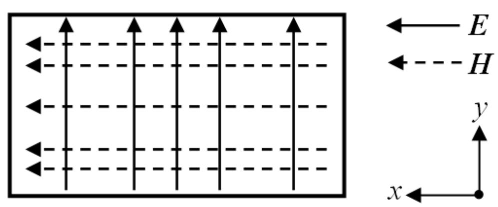

Figure 2. Field distribution inside of rectangular waveguide for TE_{10} mode

As depicted in Figure 3, a circular waveguide is a cylindrical hollow metallic pipe with uniform circular section of a finite radius r. The general properties of the modes in the circular waveguide are similar to those for the rectangular waveguide. However, in contrast to the rectangular waveguide, the dominant mode in circular waveguide is TE_{11} mode instead of TE_{10} mode. In addition, a unique property of TM_{0n} modes in circular waveguide is rapid decreased in attenuation with the increase of frequency which benefits for the application in long low-loss communication link. The other advantage is that the circular waveguide can produce dual polarization that is very important in the broadcasting with lowest attenuation [2]. The cut-off frequency of circular waveguide can be expressed below [2]-[3].

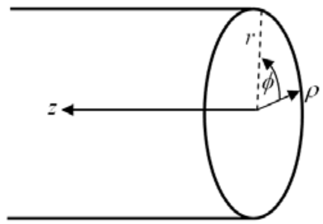

Figure 3. Illustration of circular waveguide with the radius of *r*

$$f_{c,mn} = \frac{c \cdot p'_{mn}}{2\pi r} \tag{4}$$

where p'_{nm} is the value of 2nd order of Bessel differential function, *c* is the light velocity in vacuum, and *r* is the radius of circular waveguide. Hence, the possible higher order modes for practical interests are TE_{01} and TM_{01}. The attenuation for TE_{01} mode is very low and decreases with $f^{-3/2}$. Therefore, although TE_{01} mode is not dominant, it is usually used for long distance communication lines and also for resonant cavities with very high quality factor. The electromagnetic field distribution across front section of circular waveguide at TE_{11} mode is shown in Figure 4 [3].

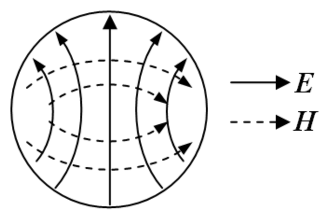

Figure 4. Field distribution inside of circular waveguide for TE_{11} mode

B. Rectangular to Circular Waveguide Transition

In order to combine the advantage of rectangular waveguide in the excitation method and of circular waveguide in the low attenuation, a rectangular to circular waveguide converter comprised of transition section is necessary. The transition section is applied to convert the dominant modes of TE_{10} in rectangular waveguide to the dominant mode of TE_{11} in circular waveguide and vice-versa as shown in Figure 5. To avoid abrupt dimensional changes and generation of higher-order modes, the minimum length of transition section should be larger than quarter wavelength. Hence, the length of complete section of waveguide converter usually is more than twice of wavelength ($2\lambda_g$) [6].

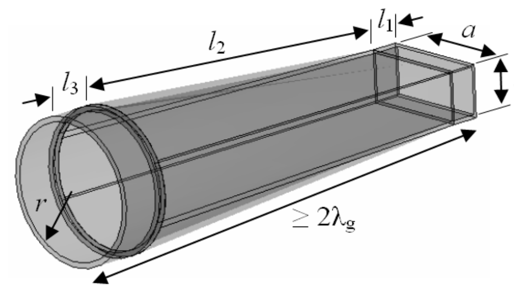

Figure 5. Rectangular to circular waveguide converter

3. Numerical Design and Analysis

A. Design Specifications

To have an optimum design, the specifications of rectangular to circular waveguide converter are as follows:

(i). The used rectangular waveguide transducer is WR284 type with *a* and *b* of 72.1mm and 34mm respectively. The transducer works on the dominant mode TE_{10} in the frequency band of 2.60-3.95GHz.

(ii). The used circular waveguide is WC284 type with the radius of 49.7mm. The desired mode of circular waveguide is TE_{11} dominant mode in the frequency band of 2.60-3.95GHz.

(iii). The length of waveguide converter should be larger than $2\lambda_g$. Here, the cut off frequency of WR284 type rectangular waveguide transducer for TE_{10} mode can be calculated using (2) and it is 2.08GHz so that the wavelength of waveguide (λ_g) is 144mm. Therefore to avoid the change of abrupt dimension that generates the higher-order modes, the minimum length of waveguide converter is 288mm [4].

(iv). The thickness of inside wall of waveguide converter can be neglected because of skin depth factor [4].

(v). The used material for waveguide converter is aluminum since it has high enough conductivity ($\sigma = 5.8x10^7$ S/m).

B. Design of Waveguide Converter

Prior to the design of waveguide converter, at first the rectangular waveguide transducer of WR284 type is numerically analyzed. Although this part is not included in the design as it is already available for the measurement, however, its numerical data is necessary as reference in the whole design of waveguide converter. The frequency response of reflection coefficient for the transducer is depicted in Figure 6. From the figure, it shows that the transducer has working frequency of 2.5–4.4GHz for reflection coefficient more than -10dB with the minimum value of reflection coefficient is -36dB achieved at frequency of 3.7GHz. It should be noted that the dominant mode of TE_{10} for rectangular waveguide (2.60–3.95GHz) is included in the working frequency of transducer.

According to the specifications previously mentioned, there are 3 stages of investigation in the design of rectangular to circular waveguide converter as illustrated in Figure 5. The first stage is to investigate the length of rectangular segment (l_1) in order to obtain its optimum length. Hence, the second investigation is to find the optimum length of transition segment (l_2) which is the main part of converter as it plays an important role in the mode conversion. Then, the last stage is to obtain the optimum length of circular segment (l_3).

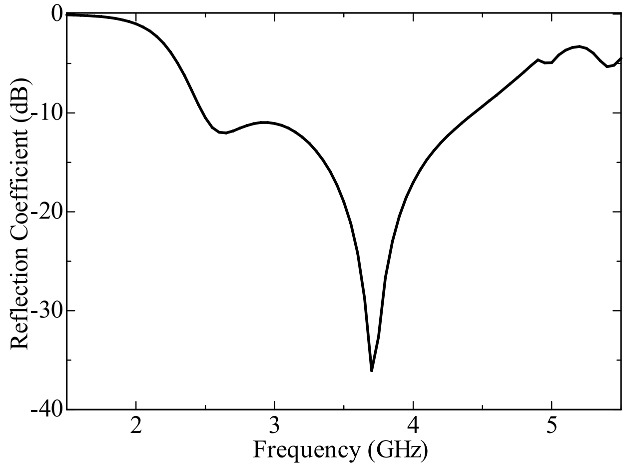

Figure 6. Return loss result of rectangular waveguide transducer WR284

In the investigation of length of rectangular segment (l_1), the length is investigated numerically to produces return loss and bandwidth that accomplish to the requirement. The values used for investigating l_1 are 5mm (l_{11}), 10mm (l_{12}), 15mm (l_{13}), 20mm (l_{14}), and 25mm (l_{15}). The range of values in 5mm interval is set for simplicity reason in the fabrication. The investigation result of reflection coefficient for different lengths of l_1 is depicted in Figure 7. It is shown that the length of rectangular segment of 20mm (l_{14}) accomplishes the specifications for required reflection coefficient and bandwidth. The working bandwidth of l_{14} ranges from 2.45-4.45GHz for -10dB reflection coefficient with the minimum value of reflection coefficient is -39.45dB achieved at frequency of 3.1GHz. Therefore, the value of l_{14} will be used to determine the length of transition segment (l_2).

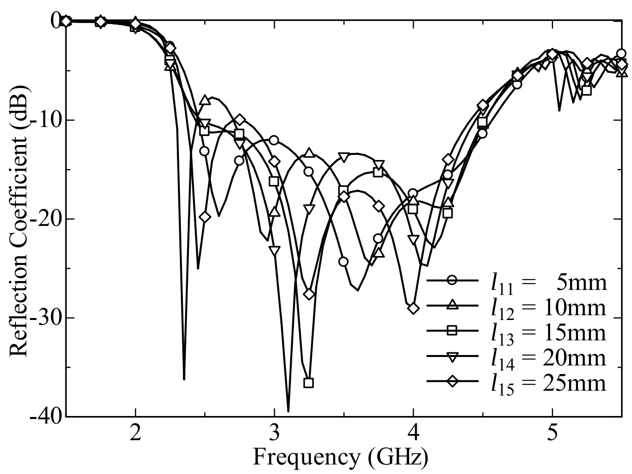

Figure 7. Reflection coefficient of rectangular segment for different lengths of l_1

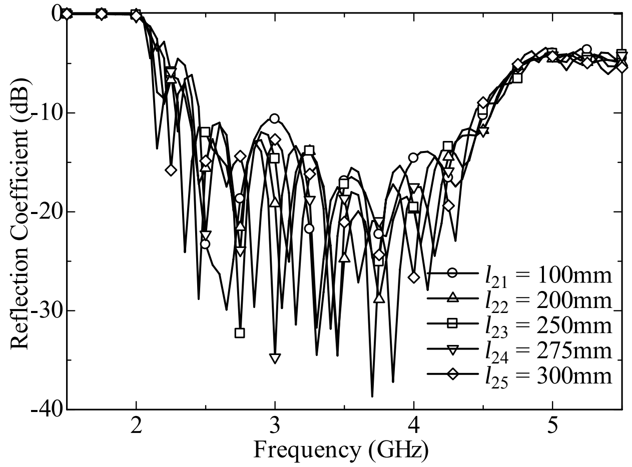

Figure 8. Reflection coefficient of transition segment for different lengths of l_2

As the next stage, the investigation to obtain the optimum length of transition segment (l_2) as the main part of converter is conducted by connecting the rectangular segment and the circular segment with radius (r) of 49.7mm. By using the length of rectangular segment (l_1) of 20mm obtained in the first stage, the investigation is carried out by varying l_2 with the value of 100mm (l_{21}), 200mm (l_{22}), 250mm (l_{23}), 275mm (l_{24}), and 300mm (l_{25}). The investigation result of reflection coefficient for different length of transition segment (l_2) is plotted in Figure 8. From the result, it should be noted that the length of transition segment of 275mm (l_{24}) has the reflection coefficient and bandwidth required by the specification. It shows that the working bandwidth of l_{24} for -10dB reflection coefficient is 2GHz ranges from 2.46–4.46GHz with the minimum value of reflection coefficient is -37.20dB achieved at frequency of 3.85GHz. Actually, the value of l_2 more than 300mm in a quarter wavelength ($0.25\lambda_g$) interval affected to the smoothness of dominant mode conversion, however, the longer of l_2 the higher cost of fabrication. As the response of reflection coefficient values for the longer of l_2 is not significant, therefore, the length of transition segment (l_2) is set to be 275mm and this will be used for the next stage.

After obtaining the length of transition segment (l_2), the last stage is to define the optimum length of a circular segment (l_3). By using the length of rectangular segment (l_1) of 20mm and the length of transition segment (l_2) of 275mm obtained from the previous stages, the investigation is conducted by varying the length of a circular segment (l_3) using values of 15m (l_{31}), 30mm (l_{32}), 45mm (l_{33}), 60mm (l_{34}), and 75mm (l_{35}). Similar to the length of rectangular segment (l_1), the values of l_3 are chosen for simplicity reason in the fabrication. The investigation result of reflection coefficient for different length of circular segment (l_3) is depicted in Figure 9. From the figure, it shows that the optimum result is obtained when the length of circular segment is 30mm (l_{32}) with the working bandwidth for -10dB reflection coefficient ranges from 2.37–4.56GHz. As the conclusion, the total length of converter that will be used for the fabrication is 335mm which accomplishes the requirement according to the theory ($\geq 2\lambda_g$).

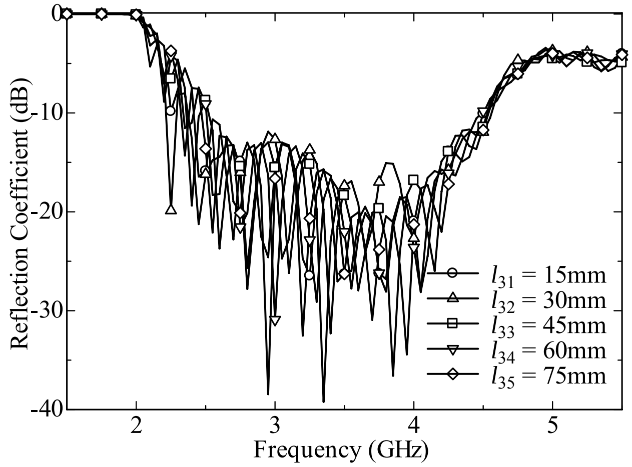

Figure 9. Reflection coefficient of circular segment for different lengths of l_3

4. Fabrication and Characterization

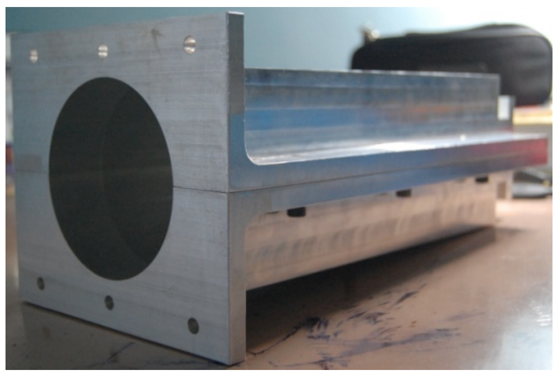

Figure 10. Picture of fabricated rectangular to circular waveguide converter

Figure 10 shows the fabricated of prototype rectangular to circular waveguide converter based on the design criteria. The prototype is fabricated using milling machine to reduce the cost of fabrication. The material used for fabrication is duralumin instead of pure aluminum used in the design process as the duralumin is easier to be processed using milling machine and stronger than the pure aluminum. The prototype consists of 2 symmetrical parts of half converters (up and bottom) connected together using bolts. As the important side of prototype for the mode conversion is the inside of converter, therefore the shape of converter outside is slightly different compared to the design. The characterization of converter prototype is carried out experimentally using Vector Network Analyzer (VNA). The experimental characterized result of reflection coefficient is plotted in Figure 11 together with the design result for comparison. It is shown that the prototype has better response of reflection coefficient compared to the design result especially for the frequency range of 2.7–3.9GHz. This can be understood the material used for prototype fabrication is duralumin that alloys of aluminum (over 90%) with copper (about 4%), magnesium (0.5%–1%), and manganese (less than l%). From the composition, therefore the conductivity of duralumin is higher than pure aluminum that affects to the reflection coefficient.

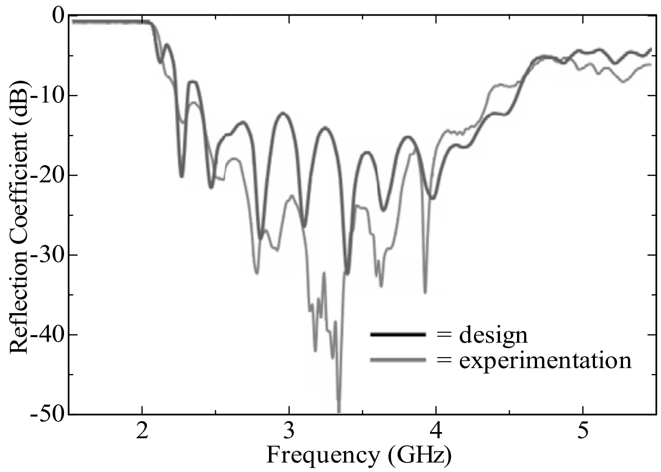

Figure 11. Reflection coefficient of measurement and design results

5. Conclusions

The rectangular to circular waveguide converter for microwave devices characterization has been investigated numerically and characterized experimentally. The converter that has working frequency of 2.60–3.95GHz has been designed for the excitation using a WR248 type rectangular waveguide transducer and then converted to a WC248 type circular waveguide. The investigation has been carried out to determine the optimum design of converter including the length of rectangular segment, the length of transition segment and the length of circular segment. From the investigation results, it has been shown that the length of transition segment plays an important role to determine the response of reflection coefficient and bandwidth. It has also been demonstrated that the converter can convert from the TE_{10} dominant mode of rectangular waveguide to the TE_{11} dominant mode of circular waveguide smoothly. Hence from the experimental characterization result, the prototype of converter fabricated by use of duralumin has shown better reflection coefficient compared to the design result especially for the frequency range of 2.7-3.9GHz due to the used material that has higher conductivity. More realistic utilization of the prototype converter to characterize the properties of circular type of microwave devices is still in progress where the results will be demonstrated later.

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