Novel rectangular-to-circular waveguide mode converter based on using one-step double-cruciform waveguide for millimetre-wave applications

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Abstract
A novel design for a TE_{10}^-mode rectangular waveguide to a TE_{11}^-mode circular waveguide mode converter based on the use of an intermediate one-step double-cruciform section is proposed. The converter achieves compactness and broadband by employing the one-step double-cruciform transition instead of the conventional multi-step transitions or smooth transitions. Due to the one-step structure, the converter achieves an extremely short-length (around 0.3λ, where λ is the wavelength at the centre frequency), which makes it suitable for highly compact systems. For verification purpose, a back-to-back connection rectangular-to-circular mode converter was fabricated and measured. The measured results show that the return loss is around 15 dB and the insertion loss is around 0.4 dB in the operating frequency band. Thus, we can infer that the return loss and insertion loss of a single mode converter are around 19 and 0.2 dB, respectively. The experimental results reasonably agree with the simulated results.

1 | INTRODUCTION

As a kind of important microwave components, waveguide transformers are widely applied in test equipment, transmission sub-systems, or antenna systems. In order to satisfy the requirements of microwave and millimetre-wave applications, various waveguide transformers, such as rectangular waveguide twists [1,2], rectangular-to-coplanar waveguide transition [3,4], rectangular-to-microstrip line transition [5,6], rectangular-to-circular converter [7–12] etc., were proposed, in which rectangular-to-circular waveguide converters, as feeder lines for horn/reflector antennas, have attracted a lot of research interest. The works of researchers are mainly focused on achieving wideband performance, compact structure, and the suppression of spurious modes. In general, in previous designs, the rectangular-to-circular converters are mainly based on two types.

The first type employs the multiple empty rectangular waveguides as shown in Figure 1, usually more than two sections, to construct the rectangular waveguide to circular waveguide converters [7–9], which relies on the wave multiple reflection between multi-step waveguide sections to achieve maximum impedance matching. Thus, these converters can easily obtain a good return loss and wideband performance. However, due to the use of the multi-step waveguides, the intermediate multi-step transition needs to be processed many times especially in the millimetre-wave bands. Besides, this will increase the time and manufacturing costs.

The second type uses the smooth-waveguides to directly connect the rectangular waveguide and circular waveguide [10–12], as shown in Figure 2. This type of converter is a simple structure with one-intermediate waveguide. But, the smooth converter easily suffers from the influence of the spurious modes, that is, higher modes are different from the fundamental mode. Moreover, this kind of converter needs several waveguide wavelengths (usually larger than 2 × λ, where λ is the wavelength at the centre frequency) to realise a wide bandwidth and obtain low return loss. Therefore, this structure will occupy large space. Furthermore, the machining of smooth waveguides is not easy.

To facilitate the application of millimetre-wave systems, attention should be paid to compact structure and wide bandwidth of the rectangular-to-circular waveguide mode converter so as to implement optimal performance with smaller dimensions. A novel rectangular-to-circular waveguide converter based on one-step double-cruciform section is
proposed to solve the aforementioned problems, which can be used as an effective alternative to create a new rectangular-to-circular waveguide converter. To the best of the author's knowledge, this is the first presentation about a one-step rectangular-to-circular waveguide converter with extremely short-length and wide bandwidth. In addition, compared with conventional designs, the one-step double-cruciform transition is easy to integrate.

## 2 | DESIGN OF DOUBLE-CRUCIFORM WAVEGUIDE MODE CONVERTER

The geometry of the proposed mode converter is shown in Figure 3. The converter is used to convert $\text{TE}_{10}$ mode of rectangular waveguide to $\text{TE}_{11}$ mode of circular waveguide. As we can see, the converter, which consists of a rectangular waveguide port, circular waveguide port and one-step transition, is a completely symmetrical with respect to the $x$-axis and $\gamma$-axis. This symmetrical structure can control the high-order mode generation [13]. In effect, the symmetry plane of perfect electric conductor (PEC), along the $x$-axis, and the perfect magnetic conductor (PMC), along the $\gamma$-axis, is used to reduce the number of modes so as to improve the conversion purity and reduce the computational time [1]. The one-step transition is double cross cruciform (marked as cruciform I and II with blue dot line and red dot line, respectively) as shown in Figure 3b. Since the converter, herein, is designed to operate from 26.5 to 38.5 GHz, the standard rectangular waveguide WR-28 ($a = 7.112$ mm, $b = 3.556$ mm) is adopted as input port. The circular waveguide is adopted as output port, which is chosen by the following equation [14].

$$f_{c,mn} = \frac{c \cdot P_{mn}}{2\pi}$$

where, $c$ is light velocity, $P_{mn}$ is a result from Bessel differential function second order and $\pi$ is radius of circular waveguide. In addition, due to the symmetry, the radius ($\pi$) of circular waveguide is selected as 4.12 mm with a dominant mode cut-off frequency of 21.29 GHz and second higher-order mode cut-off at 44.25 GHz, which cover the operating frequency band. The intermediate double-cruciform transition is most important part for the realisation of the mode conversion. Because the intermediate double-cruciform transition is not regular waveguides, there are not available closed-form expressions to analyse its cut-off frequency and field pattern. But, with proper selection of cruciform dimensions and on-axis...
angle (Θ) rotation between two branches (see Figure 3b), the mode transforming from rectangular waveguide to circular waveguide can be readily achieved. To gain a better understanding of the influence of cruciform regarding the performance of mode converter, two cruciform will be analysed, especially the rotation angle (Θ) and the thick (l) of the transition. First, we start with the rotation of the Θ, where the Θ from 10° to 80°, with the interval 10°. Figure 4 shows the results of the rotated Θ. It can be seen that when the Θ increases to 50°, the return loss gradually becomes better. In particular, when the Θ is around the 40°, the transformer obtains best value, with return loss greater than 20 dB. However, with the Θ increases from 50° to 80°, the return loss gradually deteriorates. When the Θ increases to 80°, the return loss only is better than 10 dB in the operating frequency band.

The thickness (l) of one-step transition is another important parameter because it not only affect the mode conversion but also the whole volume of the converter. In this design, we try to achieve shortest length while obtaining good performance. The thickness (l) of one-step transition is analysed from 1 to 4 mm, with the interval 0.5 mm. Figure 5 presents

![Figure 4](image1.png) Simulated return loss versus frequency for different Θ rotation

![Figure 5](image2.png) Simulated return loss versus frequency for different thickness l

![Figure 6](image3.png) Simulated results of smooth mode converter and double-cruciform waveguide

| Parameter | Value |
|-----------|-------|
| a₁        | 2.07  |
| a₂        | 1.37  |
| a₃        | 1.39  |
| b₁        | 8.29  |
| b₂        | 8.34  |
| b₃        | 11.28 |
| Θ         | 45°   |
| l         | 2.8   |

![Figure 7](image4.png) Three-dimensional view of the back-to-back rectangular-to-circular waveguide mode converter and E-field distribution at different cut-planes
the effect of the thickness on the converter. As we can see that with the increase of thickness \( l \) from 1 to 3 mm, the return loss of converter becomes better and the optimized \( l \) is around 3 mm. When \( l \) increases from 3.5 to 4 mm, we found that the serious resonance occurs at 35 and 36.8 GHz, respectively. The evaluation results reveal that for avoiding the serious resonance, the thickness \( l \) must be less than 3.5 mm. Based on the above analysis, the converter can realise good performance.

Figure 6 shows the simulated results of double-cruiform converter and smooth converter. In order to compare the performance, the smooth converter and double-cruiform converter are equal in length. It can be observed from Figure 6 that the \( S_{11} \) of smooth converter is around \(-10\) dB, the \( S_{21} \) is around \(-0.4\) dB over the whole operating frequency band from 26.5 to 38.5 GHz. The \( S_{11} \) of double-cruiform converter is less than \(-20\) dB and \( S_{21} \) is less than \(-0.1\) dB, which means the mode converting efficiency is 97.72%. Thus, the proposed converter has better performance. The best dimension parameters are summarised in Table 1.

### 3 | TOLERANCE ANALYSIS AND MEASURED RESULTS

In order to facilitate the final measurement, the proposed rectangular-to-circular waveguide mode converter adopts the back-to-back connection. Figure 7 shows the three-dimensional structure of the back-to-back converter while the
simulated E-field distributions at different cut-planes also is presented to help us understand the conversion from rectangular waveguide TE$_{10}$ mode to circular waveguide TE$_{11}$ mode. As shown in Figure 7, the TE$_{10}$ mode is successfully converted to TE$_{11}$ mode through the one-step cruciform transition.

Cruciform I and II, as critical parts, directly influences the results of the mode converter. Considering the inevitable milling errors of traditional computer numerical control (CNC) machine, quantifying the dimension of cruciform I and II is meaningful. The dimensions ($a_1$, $a_2$, $a_3$, $b_1$, $b_2$, and $b_3$) with a deviation of ±0.1 mm are considered. Moreover, the rotation angle (Ω) of cruciform II with ±1° also are analysed. As shown in Figures 8 and 9, there is a small difference of return losses. Return losses are lower than 15 dB. In addition, the bandwidth performance of the mode converter has not been influenced with the deviation of ±0.1 mm and ±1°. Therefore, the mode converter has a good dimension deviation tolerance.

To verify the design, a prototype of the rectangular-to-circular waveguide converter was fabricated according to the optimum dimension parameters given in Section 2. Figure 10 exhibits the photograph of the fabricated back-to-back converter. The prototype converter, in series connection, was measured by using an Agilent 8722EC Vector network analyzer. The measured results are presented in Figure 11 together with the corresponding simulated results for convenient comparison. From Figure 11, we can see that, the measured reflection coefficient is around −15 dB and transmission coefficient is around −0.4 dB over the frequency range from 26.5 to 38.5 GHz (with 37% fractional bandwidth). According to the measured results, we can infer that the reflection coefficient and transmission coefficient of the single transformer are around −19 and −0.2 dB, respectively. Therefore, the mode converting efficiency of the proposed mode converter is around 95.50%. The experimental results reasonably agree with the simulated ones. The difference between the simulated and measured results is mainly due to the machining and assembly errors.

Table 2 lists the comparison with some other presented rectangular-to-circular waveguide mode converters. It can be seen that the proposed mode converter has great performance. In particular, the compact size of the mode converter has an outstanding advantage when the compact structure is compulsively demanded.

In addition, 3D printing technology can be adopted to fabricate this double-cruciform mode converter, which make it very economical and the performance might be just as good. Furthermore, using 3D printing technology, the mode converter does not require additional assembly.

| Reference                  | Insertion loss (dB) | Fractional bandwidth (%) | Matching technology     | Length of the transition (λ) | Efficiency of mode conversion (%) |
|----------------------------|---------------------|--------------------------|-------------------------|-----------------------------|---------------------------------|
| Liu & Zhao [7]             | <0.1                | 50                       | Stepped waveguide       | 1.5                         | 97.72                           |
| Stuchly & Kraszewski [8]   | <0.2                | 41                       | Stepped waveguide       | 1.2                         | 95.50                           |
| Strycharz & Pia Knecki [10] | /                   | 32                       | Smooth waveguide        | 2.4                         | /                               |
| Yakan Musthofa & Munir [11] | /                   | 41                       | Smooth waveguide        | 3                           | /                               |
| This work                  | <0.2                | 37                       | Double-cruciform waveguide | 0.3                         | 95.50                           |

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**CONCLUSION**

A novel double-cruciform waveguide mode converter has been proposed, which achieves an extremely short-length, around 0.3 times guided wavelength. It can greatly reduce the whole dimension of the integration systems.

Besides, the converter obtains broadband performance, with a relative bandwidth of 37%. For verification purpose, a back-to-back sample converter was designed, fabricated and measured. The measured reflection coefficient is less than −15 dB and the transmission coefficient is lower than −0.4 dB. The measured results are in good agreement with simulated ones and demonstrate the great performance of the double-cruciform waveguide mode converter.

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