An in-line coaxial-to-circular waveguide transition at X band

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A wideband transition from the coaxial TEM mode to the TM_{01} mode of the circular waveguide with in-line input-output architecture is proposed in this paper. The transition employs multi-stage stepped impedance transformer to achieve wideband responses. Both mode transition and impedance matching characteristics are discussed in the paper. A demonstrator is developed and validated experimentally. As compared with some recently published reports, a better performance is observed. Moreover, the developed transition could facilitate the mechanical fabrication more easily. It can be found wide applications such as the circular waveguide based slot array antenna, the nondestructive detection, cracks inside the conductive pipes, and so on.

Key words: circular waveguide, coaxial line, transition, TM_{01} mode

1 Introduction

Various applications taking advantage of TM_{01} mode of the circular waveguide with circumferential discontinuities such as slots, cracks and wall thinning are extensively considered and studied [1–3]. One of the typical examples is the circumferential slot array antenna, where desired radiation characteristics are obtained with the use of the TM_{01} mode exciting [2, 3]. The fundamental or dominant mode of a circular waveguide is the TE_{11} mode. Hence, how to excite the TM_{01} mode is a basic and important issue, and a transition is necessary to excite such a mode in a circular waveguide.

In general, the simplest way to excite the required TM_{01} mode is the use of a coaxial line. To date, several studies were performed to discuss and demonstrate the transition from a coaxial line to a circular waveguide. Based on the complex power conservation technique, a case of coaxial probe feeding a circular waveguide is analyzed and verified with good experimental results [4]. In [5, 6], Galerkin's method of moment was utilized to study this kind of transition structure, and further, it was studied from measurements [7]. On the other hand, the characteristics were discussed for some potential applications [8]. To widen the bandwidth, conical coaxial line and tapered cylindrical horn was reported for radiation applications [9]. Using multistage impedance transformer to achieve bandwidth extension was a common way [10, 11], while the multistage can also be approximated as a cone to realize the same purpose [12]. It is mentioned that such a transition can be orthogonal between the coaxial line and the circular waveguide [13, 14].

Fig. 1. Configuration of the converter: $D_1 = 32.54$ mm, $h_2 = 5.2$ mm, $h_3 = 3$ mm, $h_4 = 5$ mm, $h_5 = 1$ mm

In this work, an X-band transition from the coaxial line to circular waveguide with TEM mode to TM_{01} mode is studied. Using a three-order stepped transformer, a wideband impedance matching is observed with a high efficiency, while the mode conversion between coaxial line and circular waveguide is also implemented based on the stepped transformer. Both mode conversion and impedance matching are discussed. Full-wave simulations and measurements are presented to verify the performance of the studied structure. Contributions of this work involve that we clearly formulate the operation mechanisms of this kind of transition, both from the mode matching and from the impedance matching, and shows the two matchings are critical and essential in developing such a transition. Clear advantages of the developed structure are simple thus low cost in realization since only the stepped probe is utilized to achieve both mode and impedance matchings, as compared with the one in [11]

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Fig. 2. Electric field distributions of the circular waveguide: (a) – degenerate mode I of TE_{11} mode, (b) – degenerate mode II of TE_{11} mode, and (c) – TM_{01} mode

Fig. 3. The mode conversion between the stepped coaxial line and the circular waveguide

that both stepped probe and stepped circular waveguide are employed simultaneously to realize the two matchings. On the other hand, for the demonstrator prototype transition, the stepped probe is further detailed and discussed for practical fabrication and assembling purposes.

2 Converter structure and analysis

Figure 1 shows the schematic diagram of the proposed TEM- TM_{01} transition. The basic configuration contains a 50- Ω SMA connector (I), a coaxial line (II), a transition probe or a stepped coaxial waveguide (III) and a standard circular waveguide (IV).

The circular waveguide (C65) has a diameter of 32.54 mm. To excite the TM_{01} mode at X-band, a circular waveguide with a suitable inner diameter is necessary to ensure the required TM_{01} mode is not the cutoff mode. A probe is utilized to excite the TM_{01} mode of the circular waveguide and further matched to the SMA connector. In general, such a kind of transition involves two aspects: one is the mode conversion and another is the impedance transforming; this respectively corresponds to the mode matching and impedance matching.

For the mode matching, it is known that for the circular waveguide, the dominant mode is the TE_{11} mode Fig. 2(a), which is a pair of polarization-degenerate modes, and (b) illustrate the electric field distributions of such a pair of degenerate modes. But in this study, we designate to excite the TM_{01} mode (the first higher order mode) of the circular waveguide. The corresponding electric field distribution is shown in Fig. 2(c). It can be seen the electric field lines for TM_{01} mode is radially directed,

while for a coaxial line, the dominant mode is the TEM in which its electric field lines are also radially directed. Therefore, the two different modes of the two waveguides share similar field distributions, thus by using the in-line excitation, the mode conversion between the coaxial line and the circular waveguide can be approached readily.

In this study, we use a three-order step to realize the mode conversion, as shown in Fig. 3. It is seen from Fig. 3 that the three-order step is actually a stepped coaxial line, therefore its electric field distribution could start from the stepped conductor and end at the outer conductor (circular waveguide) with its polarization varied alternatively. From Fig. 3, one can also find the stepped coaxial line is open ended, therefore, such an open-ended discontinuity could further change the field distribution, where the electric field lines are distorted and curved; some lines could start from or end at the transverse plane of the open end. It is mentioned that this is an important procedure in which the mode could eventually convert to the one corresponding to the TM_{01} mode of a circular waveguide. To this end, the mode conversion is realized. Notice that the step at the right side (corresponding to the open-loaded step) primarily functions as the mode converter here, as compared to those for implementing the impedance transformation presented below.

As shown in Fig. 1, it is a standard coaxial line for section I and in terms of the impedance matching, we characterize it based on the characteristic impedance in general, while section IV corresponds to standard circular waveguide and, it is generally discussed based on the wave impedance under a given mode, TM_{01} mode here. These are totally different two kinds of impedances and therefore, one cannot directly perform or discuss the impedance matching between them. Consequently, we directly numerical study the impedance matching by using full-wave 3D electromagnetic simulation, where a finite element method based simulator, HFSS from Ansoft inc, is employed here.

The basic matching scheme is using the stepped impedance transformer, as illustrated in Fig. 1, where for section II, it is for assembling considerations, since to fix the SMA connector to the circular waveguide, some screws are utilized. Thus the length h_1 is prescribed as

Fig. 4. Probe details in fabrication and assembling: (a) – the probe, (b) – the open end, (c) – assembled after soldering

Fig. 5. Photograph of the fabricated back-to-back prototype: (a) – the assembled structure, (b) – the probe

Fig. 6. S parameters of the transition

6 mm, and the diameter D_2 is fixed as 0.87 mm that is the same with the inner conductor of the SMA connector. Section III primarily functions as the core part of this transformation structure. Basically, it is a second-order stepped impedance transformer loaded by a reactance with open end. In this design, we would like to make a compact transition, thus the impedance transformation section, marked as lengths h_2 , (actually $h_2 - h_5$ and h_3 , should be less than a quarter-wavelength for each step. But this could lead to extra reactance and therefore, to compensate for the created reactance, a reactive

open load is employed as shown in the right-most part (marked as a length of h_4 with a diameter of D_6) in Fig. 1. It is noted that such a reactive load also plays a key role and is indispensable to the mode conversion, as presented above.

By involving the stepped and open discontinuities, the full-wave electromagnetic simulator, HFSS, is performed to present comprehensive evaluation of its electric performance. With optimal designs, the final parameters of the transition structure are determined as (units: mm): $D_3 = 1.6$, $D_4 = 6$, $D_5 = 14$, $D_6 = 12$, $h_2 = 5.2$,

Table 1. Comparisons between the proposed transition and some reported results

Ref/Year	Bandwidth (GHz)	Efficiency (%)	Fractional bandwidth (%)
This work	8–12.5	95	44
[8]/2015	9–12	–	28.6
[9]/2008	2.5–4.5	95	60
[12]/2016	3–4.2	89	33.8
[14]/2014	8.5–12	89	34.1

$h_3 = 3$, $h_4 = 5$, $h_5 = 1$ with other parameters prescribed as $D_1 = 32.54$, $D_2 = 0.87$ and $h_1 = 6$, where all parameters are rounded finally to facilitate the fabrication.

To further characterize the electric performance of such a transition, a back-to-back demonstrator is developed. Fig. 4 shows the probe details seen along the longitudinal cross section, where a commercial available SMA connector has an inner conductor diameter of $D_2 = 0.87$ mm. It is inserted into the stepped probe via a hole, while the probe is internal-fabricated as a conical hollow to solder the probe. Moreover, the internal conical hollow has a step with a depth of 1 mm and a diameter of D_6 , as described in Fig. 4(a). The open end is also fabricated as an internal conical hollow for weight reduction, as illustrated in Fig. 4(b). It is noted that to integrate the open end with the probe, the length of the open end is 1 mm longer than the designed value to be embedded into the step of the probe. Fig. 4(c) shows the assembled probe structure after soldering. It is soldered the inner conductor of the SMA connector first, and then the open end is integrated with the probe by soldering the brim, as depicted in Fig. 4(c).

The fabricated prototype is shown in Fig. 5. Measurements are carried out by a vector network analyzer with full two-port calibrations. Fig. 6 shows the measured results together with the simulated data for performance comparisons. It is seen from Fig. 6 that the return loss is better than 10 dB over the X band and the conversion efficiency is almost more than -0.22 dB (95 %). It is found there are some discrepancies between the measurements and simulations, where a slightly higher insertion loss is observed. It is noted that here the insertion loss describes the whole loss of the back-to-back structure that means the SMA connectors, the transition probes and a section of circular waveguide are all involved. It is believed the extra loss with the maximum value of approximately 0.6 dB near 8.5 GHz could be primarily attributed to the loss of the two back-to-back SMA connectors since in simulations, a wave port is applied to the left side of section II in Fig. 1, yielding the loss of the SMA connector without being involved. On the other hand, the return loss is also degraded as compared with the one from simulations. This may be arising from the soldering of the open end since as referred to Fig. 5(b), it is seen extra solder is attached to the open end. Another reason for this degraded return loss lies in the assembling tolerance espe-

cially for the gap h_5 shown in Fig. 1. But in general, the achieved performance is good in the band of interest, and the measurements are in agreement with the simulations reasonably.

Table 1 lists the performance comparisons for the proposed design and some recently published results. It can be observed that the fabricated prototype features wide-band response and good efficient mode-conversion capability. Furthermore, the achieved bandwidth is superior to those published designs. On the other hand, the use of stepped probe could facilitate the mechanical fabrication more easily in implementation. As compared with the contribution in [11] by using the stepped probe and correspondingly, stepped circular waveguide in the transition section, only a simple stepped probe is presented, thus could reduce the cost in realization and be featured as the advantage of this work. On the other hand, it seems the demonstrator in [11] requires extra transitions or structures to facilitate the measurements.

3 Conclusion

A wideband transition between the coaxial TEM mode and circular waveguide TM_{01} mode is presented in this paper. Theoretical analysis based on the methods of discontinuity, mode conversion and impedance matching is discussed. A prototype at X band is designed and tested, and good consistency is observed between simulations and measurements. It is believed the studied structure can find many applications in practical engineering.

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