ULTRA-BROADBAND HIGH EFFICIENCY MODE CONVERTER

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Abstract—In this paper, we develop a small-sized mode converter with high performance, high conversion efficiency and instantaneous bandwidth as high as 55%. This mode converter transforms energy from the TM01 first high-order mode towards the fundamental TE11 circular waveguide mode The proposed structure increases the free spurious operating bandwidth in comparison with the existing results in literature. An X/Ku-bands experiment prototype unit was designed, ensuring practical return losses better than 28 dB and insertion losses less than 0.1 dB (conversion efficiency > 98.8%) within the entire frequency bandwidth ranging from 9.25 GHz to 16.25 GHz The presented architecture offers useful features such as very wide bandwidth, small size, easy achievement as well as excellent performance, which makes it very suitable for High-power microwave (HPM) sources that generate the TM01 circular waveguide mode. In these cases, the TE11 mode is needed since it has a convergent radiation pattern able to drive conventional antennas. Moreover, this compact concept is fully scalable to any millimeter frequency band.

1. INTRODUCTION

The generation of high order modes in circular waveguide is useful for some applications. For example, TM01, TE21 and TE01 modes excited in circular waveguide are used in tracking feed subsystem for producing

difference pattern. In addition, several high power microwave (HPM), generators such as the oscillators of virtual cathode (vircators), the relativists backward wave oscillators from reflected waves (BWOs) and the magnetically insulating transmission-line oscillators (MILOs) [1], generate azimuthally symmetric output modes with the TM01 circular waveguide mode, and even the coaxial line transverse electromagnetic mode TEM. If these modes are directly radiated to the space from the waveguides output, a doughnut-shaped radiation pattern will be produced, with a clear absence of signal in the axis (bore-sight) due to the fact that the transverse electric field is null in the axis (undesirable conical radiation pattern). However, in a multitude of applications, the TE11 circular waveguide mode is used since it has a well defined polarization together with a convergent radiation pattern similar to "Gaussian shape" of a hybrid HE11 mode corresponding to a corrugated circular waveguide. In this sense, and if necessary, we can always transform the TE11 mode towards the HE11 mode in a relatively short physical convert length and in efficient way. Therefore, the mode converter is always needed between the source and the antenna to convert the TM01 to TE11 for high power transmission systems. An interesting survey of different configurations that achieve mode converters to generate TM01 mode in circular waveguide is found in [2–10]. Generally, the majority of TM01-to-TE11 mode converter designs have been proposed with serpentine configuration to realize high conversion efficiency, but the converter length is generally quite long [2–7]. A mode launcher exciting TE11 circular waveguide mode from the TEM coaxial mode has been presented in [8]. It has the virtues of co-aligned ports, a compact structure, and easy manufacturing. Such a design also can be used to convert the TM01 mode into the TE11 mode, by adding a simple TM01-TEM transition being embodied in it. In [9], a TM01-TE11 has been realized with an inserted section of a rectangular waveguide among a circular waveguides by way of a TM01 mode. In such cases there is a discontinuity and a complexity to provide breakdown phenomenon for high power transmission. A TM01-TE11 circularly polarized (CP) mode converter based on a non uniform configuration has been described in [10], which is suitable for designing compact and axially aligned CP launching systems. However, most of them are not fully satisfactory due to their performance limitations in terms of frequency bandwidth, conversion efficiency as well as an inherent electrical degradation, which is mainly caused by the interaction between higher order modes. In the high power microwave setup equipment these TM01-TE11 mode converters are often based on the concept of dual bend [2–7]. Nevertheless, the output and the input of the latter are not

aligned in the same axis which affects the compactness and robustness
of the system and may impede many important applications. In order
to overcome the aforementioned shortcoming, this paper presents a
very wide band mode converter that has no bended waveguide. It
is formed by a linear structure that transforms the TM01 circular
waveguide mode onto the dominant TE11 mode which provides high
conversion efficiency along with a very high power handling capacity.
Fig. 1 shows the whole structure of the TM01-to-TE11 mode converter.
This structure employs an intermediate mode TEM in the transition
between TM01 and TE10. This coaxial line provides natural isolation
while acting as a mode filter between the device ports.

Assuming that the TM01 mode excites the structure from the left

(a)

(b)
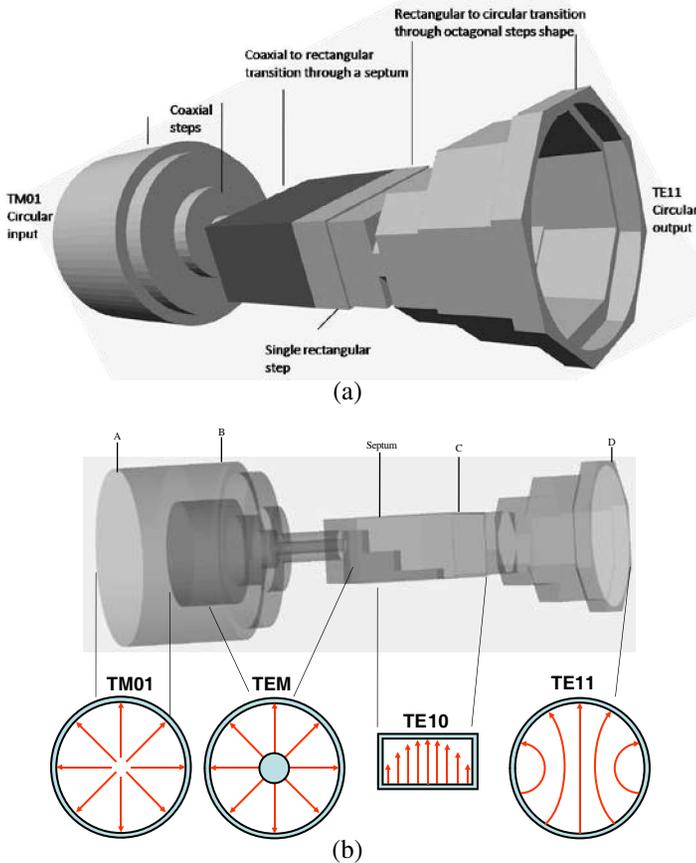
Figure 1. (a) Three dimensional view of the mode converter structure.
(b) Mode converter internal view and the propagated fundamental
modes in various waveguide sections.

part of Fig. 1, the energy is transmitted from the circular waveguide
input into a short multi-stepped coaxially shaped transformer.
This transformer couples a stepped coaxial-to-rectangular magnetic
waveguide launcher through three sections of a septum. The use of
this new architecture assures high performance with good experimental
results. Indeed, the return loss is better than 35 dB and the
insertion loss is less than 0.1 dB over the entire extended 55%
bandwidth (9.25–16.25 GHz). To the best of our knowledge, the
proposed mode converter is a drastic improvement of the existing ones.
This architecture offers several advantages such as easy fabrication,
low losses, low manufacturing cost, and a very short size. The
original contribution in this design is the specific incorporation of two
intermediate modes in order to isolate without ambiguity two TE11
circular modes in the ports of interest, and eliminate the possible
feedback loops effectively across the higher order modes propagation.
During the design steps of the mode converter, several aspects and
criteria [9] have been taken into account: high conversion efficiency,
very broad bandwidth, good impedance matching in the access
interface ports, input TM01 mode purity, output TE11 mode purity,
coalignment input-output in the same axis, and other electrical and
mechanical aspects that are highly desirable and must be considered
during the design and manufacturing processes.

2. MODE CONVERTER DESIGN

Due to the fact that in a circular waveguide the TM01 mode has a
higher cutoff frequency higher than the fundamental TE11 mode, it
is impossible to make the direct conversion without any reflection in
the signal to be transmitted. The mechanical alternative proposed
in this work initially allows the conversion of the TM01 mode of
the circular waveguide to the TEM coaxial transmission line mode,
which has a cutoff frequency equal to zero. The intrinsic separation
of the mode of the coaxial line might then be used in the mutual
isolation between the modes of the output and the input. This
philosophy divides the design into two parts: the first part transforms
the TM01 circular mode towards the TEM coaxial mode, and the
second one transforms the TEM mode to the TE11 circular mode.
Unfortunately, the conversion TEM-TE11 cannot be obtained in wide
band, due to the proximity between the cutoff frequencies of the
two modes, TM01 and TE11 circular waveguide modes. Therefore,
the second part was realized using an intermediate mode TE10 of
rectangular waveguide, therefore, it was necessary to design an axial
intermediate TEM-TE10 converter that was feeding a later TE10-TE11

conversion. Fig. 1 shows a 3D internal view of the whole device of
the mode converter TM01-TE11 together with the configuration of
the mode kinds in the different sections. Taking into account that
the TM01 mode comes on the left part of the structure, the energy is
transmitted firstly in a section of coaxial line formed by four transitions
as depicted in Fig. 2. This specification allows excellent characteristics
of TM01-TEM conversion in a frequency bandwidth greater than 55%.
Subsequently, a transition between the coaxial line and rectangular
waveguide will be designed using a septum of at least three sections,
which allows a high TEM-TE10 conversion efficiency in a frequency

(a)

(b)
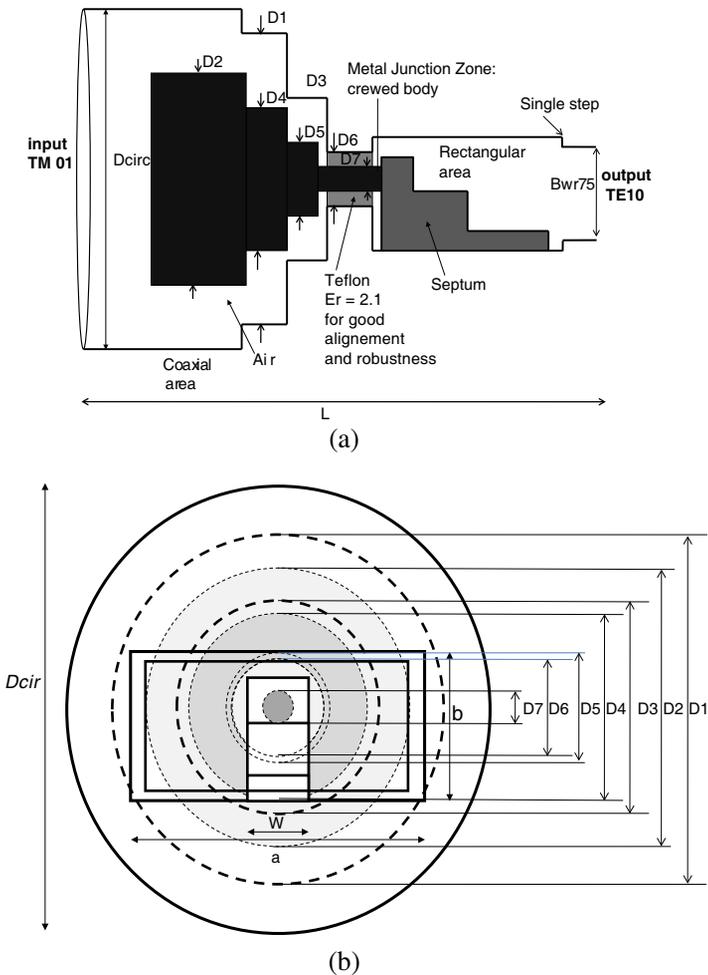
Figure 2. Circular to rectangular waveguide transition through
coaxial steps. (a) Longitudinal section view. (b) Cross section view.

bandwidth superior to 55%. Fig. 4 illustrates the important part of the mode converter; it is composed of an octagonal intermediate transition from a rectangular to a circular waveguide, which allows a TE10-TE11 conversion in a frequency bandwidth of an octave with no evidence of higher order mode excitation The feature of ultra-broadband performance is achieved mainly due to the use of a septum transition from coaxial to rectangular waveguide, that allows a very wide bandwidth application, as well as by using an octave bandwidth rectangular-to-circular transformer based on octagonal shaped sections similar to that reported in [11].

The mode converter design structure is simulated and optimized as two individual parts. The first one is the conversion from the circular TM01 mode to the rectangular TE10 mode, through the coaxial section and together with the septum sections, and the second one is the transition from the rectangular TE10 mode to the circular fundamental TE11 mode through the octagonal sections. Each body of the design was optimized as an independent part, and then put together in order to carry out the final response of the whole mode converter.

Firstly, The TM01 to TE10 mode launcher has been optimized to achieve the purity of the desired TM01 mode in circular waveguide and suppression of undesired modes in all of the frequency bandwidth ranging from 9.25 GHz to 16.25 GHz. Secondly, the octagonal TE10 to TE11 transition has been optimized to achieve an octave frequency bandwidth easily with a return loss better than 35 dB. When connecting together both parts of the mode converter structure, the final electrical performance of the mode converter is kept similar to that of the first part since the second part exhibits transparent electrical performance. For this reason, each individual part must be carefully designed in such a way that the individual performances have to be maximized in order to get a strict control on high order mode generation. Each part of the mode converter has been analysed to achieve the purity of the desired modes and suppression of undesired modes. We have found out that all the coupling of the desired and the undesired modes is kept bellow 100 dB in the bandwidth of interest. In addition, in order to ensure a good alignment and robustness of the coaxial inner conductor, the Teflon was used as a dielectric material support in the transition part from the small coaxial to the septum as shown in Fig. 2.

To better explain this concept, we are going to propose a more detailed description of the intermediate modes that appear in the structure of Fig. 1. Table 1 shows the cutoff frequencies of all the modes that exist in the different sections of the mode converter. Part A shows the cutoff frequencies of all the modes that can be excited in

Table 1. Mode distributions along the different waveguide sections according to Figure 1.

Section	Generated modes	Gutoff frequency in GHz
	TE11	6.27
	TM01	8.19
	TE21	10.4
A	TM11	13.05
	TE01	13.05
	TE31	14.31
	TM21	17.5
B	TEM	0.0
	TE10	7.88
C	TE20	15.77
	TE01	15.77
	TM11	17.64
	TE11	7.95
	TM01	10.38
D	TE21	13.19
	TE01	16.54
	TM11	16.54

the circular waveguide of the input up to the first mode beyond the desired frequency band. It can be observed that other five unwanted modes can exist in this waveguide. Consequently, trying to convert directly to the TE11 mode will excite necessarily also the modes TE21, TM11 and TE31. These previously mentioned undesired modes absorb a quantity of energy, thus, deteriorating the performance of the device. Nevertheless, we can avoid all these modes converting the TM01 mode to the TEM mode. The next higher order mode that would be excited by these means is the TM02 mode, which has a cutoff frequency of 2.5 for the TM01 mode.

The region of the TEM mode begins, in the converter, in the same diameter as the waveguide A, fitting towards the smallest diameter of the waveguide B. This smaller diameter is necessary to remove the possible propagation of the TE11 coaxial transmission line mode of a frequency beyond the band of interest; for this reason, this latter acts as a shock of the TE11 mode when it is excited in the output line of the waveguide. The isolation is fundamentally determined by the quotient of the superior edge of the operation bandwidth and the cutoff frequency of the TE11 mode, and is proportional to the length

divided by the diameter of the section. In these conditions, the energy propagates along the central conductor of the hybrid rectangular waveguide (transition across the septum). While the central conductor is in the axis, the TEM mode was found to. Similarly, in the interspace between the septum edge of the rectangular waveguide and the coaxial line, the TE11 coaxial mode together with the TE10 mode of the open rectangular waveguide C is excited. This TE11 mode cannot propagate again within the coaxial section with a smaller diameter, and is caught between the small coaxial and the septum. The choice of the appropriate dimensions in this region provides a transition with a wide frequency band between the incident TEM mode and the transmitted TE10 mode of rectangular waveguide. The most problematic mode is the TM11 rectangular waveguide mode, which corresponds to the TM01 circular waveguide mode. The TM11 mode is excited by the septum but keeps its evanescent quality in the rectangular waveguide. Therefore, only the TE10 mode exists in the end of the rectangular waveguide. A rectangular-to-circular transition (part D), through four intermediate octagonal shape sections, allows the TE10-TE11 conversion in a frequency bandwidth in the order of an octave, and avoids the excitation of higher order modes. The newly proposed alternative of the mode converter can also be used to convert the TM01 mode of the circular waveguide to the coaxial TEM mode since they are very useful for many sources of high power microwave applications. It even can be used as a mode launcher of a circular TM01 mode from

Table 2. Mode converter physical dimension values.

Parameter	Value (mm)	Parameter	Value (mm)
A_{wr}	19	$d6$	4.62
B_{wr}	9.5	$D7$	1.98
a	13.32	$l1$	12.92
b	10.12	$l2$	3.59
w	4.09	$l3$	2.74
d_y	5.9	$l4$	9.95
D_{cir}	28	$l5$	22.44
$d1$	24.44	$l6$	5
$d2$	16.68	$l7$	9
$d3$	13.36	$l8$	3.7
$d4$	10.98	$l9$	2.76
$d5$	6.04	$l10$	10.73
L	56.6		
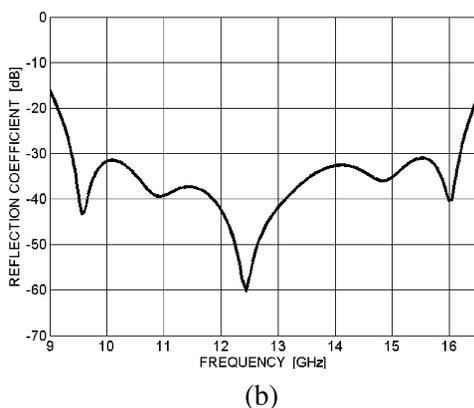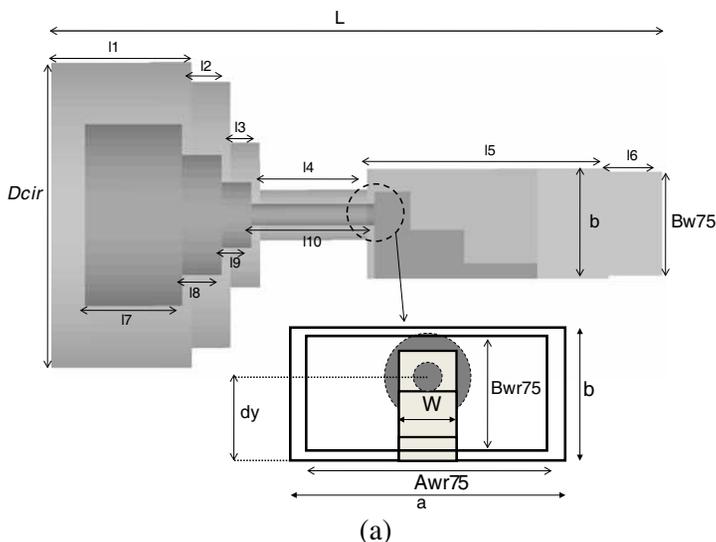
Figure 3. (a) TM01 to the TE10 rectangular waveguide mode converter geometry dimensions. (b) Simulated reflection amplitude of the TM01 to TE10 converter.

the TE10 rectangular waveguide fundamental mode. Fig. 3 shows an internal view of the TM01 to TE10 transition along with its simulated reflection coefficient amplitude.

The geometry dimensions of the TM01 to TE10 mode transformer, according to the indication shown in Fig. 2 and Fig. 3(a), are illustrated in the Table 2. The total length ($L = 56.6\,\text{mm}$) of the TM01 circular to TE10 rectangular mode transformer is as short as $2.4\lambda_0$, with λ_0 being the wavelength at the center frequency (12.75 GHz);
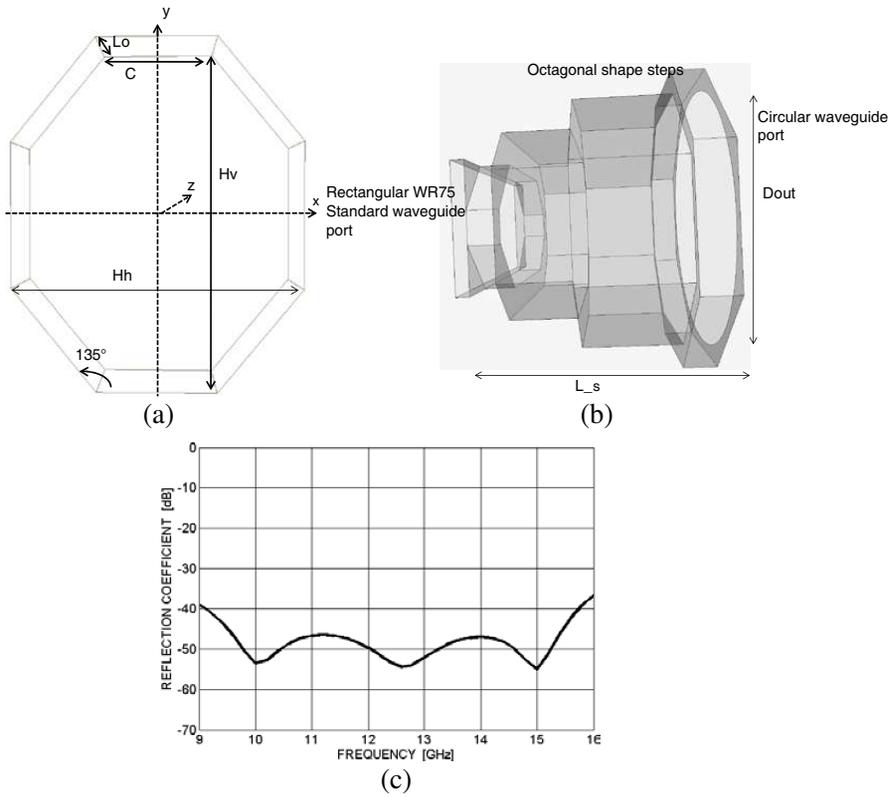
Figure 4. (a) Octagonal waveguide cross section and design parameter definition. (b) Rectangular to circular waveguide transformer through four intermediate octagonal shape steps. (c) Simulated reflection amplitude of the octagonal transformer.
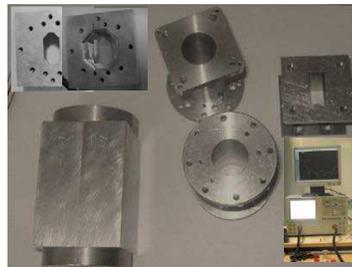
Figure 5. View of the assembled back to back mode converter.

Table 3. Rectangular to circular transformer physical dimensions according to Figure 4.

Parameter	Value (mm)	Parameter	Value (mm)
D_{out}	22.00	$c3$	10.84
$c1$	11.95	H_{h3}	22.1
H_{h1}	19	H_{v3}	19.45
H_{v1}	9.5	L_{o3}	7.97
L_{o1}	2.32	$c4$	9.75
$c2$	15.9	H_{h4}	23.54
H_{h2}	22.1	H_{v4}	23.54
H_{v2}	13.62	L_{o4}	2.7
L_{o2}	5.05	$L_{\_}s$	18.06

thus, a dramatic size reduction is obtained without degradation of the matching capabilities. To complete the mode converter device we have joined together with the first previous part the second body formed by the rectangular to circular transition through four intermediate octagonal shaped steps as shown in Fig. 4 together with its simulated input and output return losses. The physical geometry dimensions of the four octagonal shape transformer are given in Table 3. The total length of the whole structure of the mode converter, from TM01 circular input mode to TE11 output circular port, is the sum of lengths of both parts ($L + L_{\_s} = 74.6$ mm), thus showing a good improvement in term of size reduction and compactness of the previous reported bulky devices. Photographs of the assembled mode converter along with different transition blocks are shown in Fig. 5.

3. RESULTS AND YIELD ANALYSES

To validate the previous concepts, two device prototypes were achieved for X/Ku-band by using milling technique based on alumagal-6850. All the measurements have been taken with a 2-port vector network analyzer PNA E8364A from Agilent technologies. The purity of the TE11 output circular mode has been checked by experimental measurement of the mode converter by placing two similar mode converters back to back through the input circular port. Furthermore, two high performance circular-to-rectangular waveguide (WR75) transitions through octagonal shaped steps, similar to that used in the mode converter structure, were achieved for the measurement

purposes. For this reason, a WR75 TRL (Thru-Reflect-Line) was carried out to calibrate the Vector Network Analyzer.

Figure 6 and Fig. 7 show the measured return losses for both ports with their respective simulation generated by the mode matching tool μWave-Wizard [12]. The comparison of the measured and simulated insertion losses is shown in Fig. 8. As it can be observed in Figs. 6, 7 and 8, the return losses are in the order of 28 dB in both modes TM01 and TE11 along with measured insertion losses less than 0.1 dB, giving rise to a conversion efficiency of 98.8% in a fractional bandwidth superior to 55%.

In order to control the robustness of the design and, consequently,
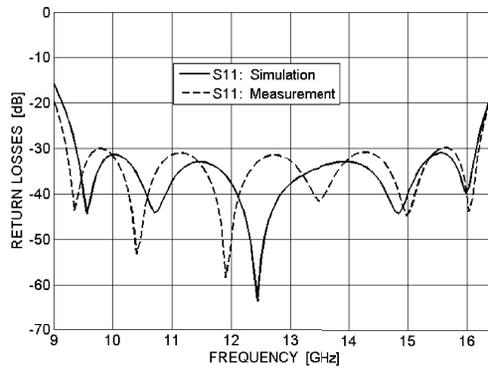
Figure 6. Simulated and measured input TM01 circular reflection of the TM01 to TE11 mode converter.
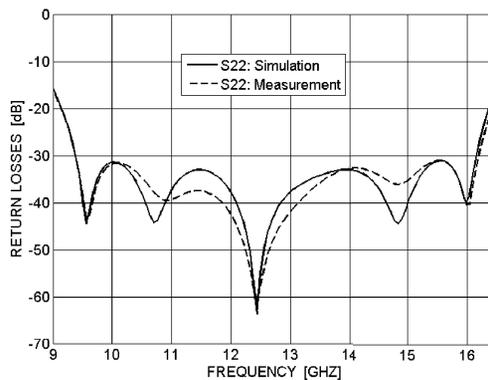
Figure 7. Simulated and measured output TE11 circular reflection of the TM01 to TE11 mode converter.
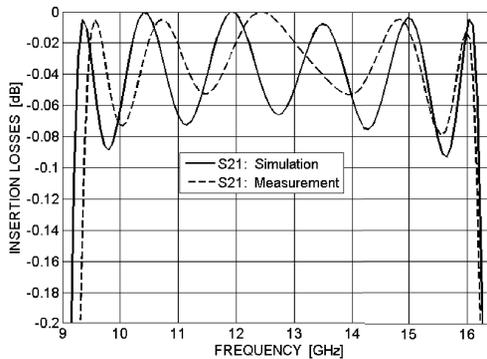
Figure 8. Simulated and measured transmission of the TM01 to TE11 mode converter.

the mechanical tolerance, a detailed sensitivity analysis has been carried out where a tolerance of ± 0.05 mm has been allowed in all the geometry dimensions of the device. The design is strongly robust to the mechanical tolerance.

4. CONCLUSION

A TM01-TE11 circular waveguide mode converter has been designed, machined and tested, by using as intermediate structure coaxial lines rectangular waveguide and octagonal shape steps, covering a frequency bandwidth of over 55%, with return and insertion losses in the order of 28 dB and 0.1 dB, respectively. The presented mode converter exhibits a good agreement between experimental and simulated results with no evidence of higher order mode excitations. This greatly improves previous reported results in term of bandwidth versus overall length. The resulting mode converter has an extremely good performances which can be achieved even in mass-production. This is due to the simplicity of its design. Moreover, the design has the best measured performances reported to date in literature. A yield analysis has been carried out allowing mechanical tolerance that validates the compactness and robustness of the design in the X/Ku-band.

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