A compact rectangular waveguide TE10 to TE20 mode converter with coplanar and codirectional configuration

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Abstract

A compact rectangular waveguide TE10 to TE20 mode converter is proposed in this paper. It consists of a dominant mode waveguide and an overmoded waveguide connected with coplanar and codirectional configuration to promise a compact cross section. A septum is inserted into the overmoded waveguide to divide it into two channels. The converter utilizes a Riblet-hybrid-like structure and two humps inserted in narrow walls of each of the two channels. The inherent 90-degree phase of the hybrid together with another 90-degree phase difference between the two channels created by the humps can realize half-wavelength phase relation and excite TE20 mode. The cross section size of cavity structure of the mode converter is about 1.52 \( \lambda \times 0.61 \lambda \) at center frequency of 9.5 GHz. Tested results demonstrate that within a fractional bandwidth of 3.3\%, the mode conversion efficiency is better than 97.7\% with a return loss of larger than 20 dB. The peak power capacity is larger than 470 kW at common air condition.

Introduction:

Dominant mode transmission lines and devices are usually utilized in normal low-power applications to maintain high transmission efficiency and avoid unnecessary higher order mode excitation. However, in high power microwave applications, where higher order modes are usually selected as the operation mode to decrease field strength and avoid RF breakdown. Thus, many kinds of mode converters are required to realize the excitation and extraction of higher order modes. Among these, rectangular TE10 to TE20 mode converter is basic and has been utilized as an intermediate employed in various applications, such as TE01 and TE21 launchers [1-6].

The existing TE10 to TE20 mode converters can in general be divided into the following types: (1) the “jog converter” composed of two oppositely oriented 45° bends, with a circular TE01-mode bend to realize mode coupling [1, 7, 8], (2) the right-angled H-plane converter composed of an overmoded waveguide and
a standard one with one port short-circuited to realize mode excitation with lateral wall coupling [2, 3, 9, 10], (3) the converter with input and output ports in different planes, utilizing a coupling aperture to realize mode conversion [4, 11], (4) the converter utilizing power division and 180° phase difference between two paths by different path length or opposite transition structure [5, 6], (5) the converter utilizing periodic dielectric rod arrays in a waveguide to realize unique dispersion property and mode conversion [12, 13].

The existing structures present a characteristic that the input and output channels locate in different planes and/or different directions, or the longitudinal dimension is too long, which bring bulky volume or inconvenience for connection and assembly in system applications. In this letter, an X-band rectangular waveguide TE₁₀ to TE₂₀ mode converter with coplanar and codirectional configuration is proposed. Its structure is simple and the fabrication is easy to conduct. Its compactness can be significantly improved.

Working Principle of the Mode Converter: According to the mode characteristics, the most common method to realize mode conversion from TE₁₀ to TE₂₀ is by dividing the TE₁₀ signal from input port into two transmission channels, and with an introduction of some phase shift mechanism, different lengths of paths or different transmission coefficients for example, to match the half-wavelength phase relation. However, by this means, either the longitudinal dimension is too long, or the cross section is not compact.

In this letter, a compact planar structure that a standard single mode waveguide is asymmetrically connected to an overmoded waveguide is proposed. A septum is inserted at the central axis of the overmoded waveguide. The converter can be divided into two parts, as shown in Fig. 1. Part I contains the input dominant mode waveguide and the overmoded waveguide truncated at the beginning of septum. The remaining portion of the overmoded waveguide is viewed as the part II. In part I, the input section with an asymmetric connection to the oversized waveguide will act in a similar manner as that of a Riblet hybrid, where the isolated port is short-circuited. Consequently, the input TE₁₀ mode is split into TE₁₀ and TE₂₀ modes with equal amplitudes. This fits in with the short-circuited boundary of the isolated port. With the addition of the septum, the signal in the overmoded waveguide is divided into path A and path B. If the length of overmoded waveguide of part I is properly designed, the signals enter into path A and path B can exhibit equal amplitudes and 90-degree phase difference. In part II, if another 90-degree phase difference can be given between the two paths, then, the recombined signal with equal amplitudes and 180-degree phase difference will be a TE₂₀ mode. In other words, mode conversion from TE₁₀ and TE₂₀ modes can be realized.

![Fig. 1 Simulation model and result of phase difference between the two transmission channels.](image)
The overall structure of the proposed mode converter together with its dimensions is given in Fig. 2. By utilizing a Riblet-hybrid-like structure and two humps inserted in path A and path B, an inherent 90-degree phase of the hybrid and another 90-degree phase difference between the two paths can realize a half-wavelength phase relation for exciting TE$_{20}$ mode. Moreover, benefited from the phase relation, TE$_{10}$ mode formation can be prohibited. In other words, high efficiency TE$_{10}$ mode to TE$_{20}$ mode conversion can be achieved.

**Fig. 2** Structure model of the TE$_{10}$ to TE$_{20}$ mode converter.

Compared with the structure that the input waveguide locates at center of the overmoded waveguide with phase shift of two transmission channels realized by different channel lengths or different channel characteristics, the proposed structure can be more compact. In this proposed converter, the phase shift introduced by the hump structures is 90 degrees, half of the conventional structure, the left 90 degrees are inherently created by the Riblet-hybrid-like structure. Thus, the longitudinal length or cross section can be reduced.

It should be noted that in order to conduct the mode conversion, strict phase relation should be met at the coupling section of overmoded waveguide in part I, and also path A and path B in part II. Besides that, part I is a transformation of Riblet hybrid. The isolated port is short-circuited, which brings in difficulty for impedance match. The phase relation match and impedance match give a relatively narrow bandwidth for the mode converter. The bandwidth can be improved from these two aspects. Namely, multiple stages phase relation and impedance match structures can enhance the bandwidth to some extent. The expense is longer longitudinal size. The objective of this paper is compact volume, where only single stage match structures are utilized.

**Simulation Results of the Mode Converter:** The TE$_{10}$ to TE$_{20}$ mode converter is established as above mentioned. Its $S$-parameters are simulated and given in Fig. 3. It is demonstrated that the mode conversion efficiency is better than 97% within a fractional bandwidth of 4.4%, with a return loss of larger than 21 dB and a mode isolation of larger than 15 dB.
The peak power capacity of this mode converter is also analysed based on the simulation. It should be noted that the mesh refinement setting on the corners of the structure which reduces the maximum size of the mesh generation is performed to promise the accuracy of the field calculations. When a power of 1 W is incident, the E-field distribution of the structure is illustrated in Fig. 4. From the plot of field distribution, the phase difference relation created by the hump and resonator structure is shown clearly. The mode conversion is then finished. The maximum E-field appears in the left transmission channel and is approximately 4.26 kV/m. If a breakdown threshold of 30 kV/cm for a single-pulse case in dry air at a pressure of one atmosphere is considered [14], the breakdown power threshold of the circulator can be predicted to be 500 kW. It should be noted that if the working condition is replaced by vacuum, which is the usual condition of HPM applications, the RF breakdown threshold can be increased by dozens of times. Then, the mode converter can exhibit a power capacity of several hundred MW.

Test of the Mode Converter: Two prototypes of the mode converters are fabricated, a photograph of which is shown in Fig. 5. The cross section size of its cavity structure is about 1.52 λ x 0.61 λ at center frequency of 9.5 GHz. Its total length is about 8 cm. The two prototypes are back-to-back connected and tested by a VNA. Fig. 6 illustrates the simulated and tested results of S-parameters for comparison. The tested results agree well with simulations. The existing slight deviation results from the processing and assembly errors. The tested results show that from 9.32 to 9.63 GHz, the return loss is more than 20 dB. The insertion loss
of single converter is less than 0.1 dB, which corresponds to a conversion efficiency from TE\textsubscript{10} to TE\textsubscript{20} mode of 97.7%.

![Prototype of TE\textsubscript{10} to TE\textsubscript{20} mode converter.](image)

**Fig. 5** Picture of the prototype of TE\textsubscript{10} to TE\textsubscript{20} mode converter.

![Tested and simulated S-parameters of the back-to-back connected mode converters (Sim. stands for simulation). The high-power tested waveforms.](image)

**Fig. 6** Tested and simulated S-parameters of the back-to-back connected mode converters (Sim. stands for simulation). b The high-power tested waveforms.

The mode converter is high-power tested utilizing a klystron at 9.35 GHz with a pulse width of 100 ns and a repetition frequency of 10 Hz. The incident wave and transmitted wave are measured utilizing directional
couplers before and after the mode converter. Attenuators are adopted at the coupling channels to make the signal amplitudes within safety range of a peak power meter. According to the recorded waveforms of the peak power meter, whether or not the RF breakdown appears can be judged. The high-power test results show that under an input power of 470 kW, which is the maximum output power of the klystron, RF breakdown doesn’t occur, as shown in Fig. 7. The simulated peak power capacity is about 500 kW, which is beyond the maximum output power of the source.

![Fig. 7 The high-power tested waveforms.](image)

Table 1 provides comparisons with previous works. The converters in [3, 4, 6, 9, 11] don’t possess coplanar and codirectional configuration. The converters in [5, 8, 12] suffer from difficult fabrication process because of bend waveguides or dielectric rods. Furthermore, they can also exist the problem of lower power capacity or longer longitudinal size. It is demonstrated that overall the mode converter has the merits of compact volume, coplanar and codirectional configuration, high power capacity and easy fabrication.

**Conclusion:** In order to conduct rectangular waveguide TE10 to TE20 mode conversion in a compact volume, a planar structure with coplanar and codirectional configuration is proposed. By utilization of Riblet-hybrid-like and two-hump phase match structures, high efficiency mode conversion can be achieved. Its compactness is significantly improved compared with previous works, with satisfactory power capacity. Its fabrication is simple and it has great potential in the field of high power microwave mode conversion applications.

**Table 1:** Comparisons with previous works.

<table>
<thead>
<tr>
<th></th>
<th>Coplanar configuration</th>
<th>Codirectional configuration</th>
<th>Center frequency</th>
<th>Simulated bandwidth</th>
<th>Inner cavity dimensions</th>
<th>Power capacity</th>
<th>Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3]</td>
<td>Y</td>
<td>N</td>
<td>31 GHz</td>
<td>21% (&gt;99%)</td>
<td>1.96 λ×0.43λ (Length: 2.5 λ)</td>
<td>high</td>
<td>easy</td>
</tr>
<tr>
<td>[4]</td>
<td>N</td>
<td>Y</td>
<td>33 GHz</td>
<td>30.3% (&gt;97.5%)</td>
<td>2.21×1.54λ (Length: 2.41 λ)</td>
<td>low (corners)</td>
<td>difficult (corners)</td>
</tr>
<tr>
<td>Coplanar configuration</td>
<td>Codirectional configuration</td>
<td>Center frequency</td>
<td>Simulated bandwidth</td>
<td>Inner cavity dimensions</td>
<td>Power capacity</td>
<td>Fabrication</td>
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<td>[5]</td>
<td>Y</td>
<td>Y</td>
<td>262.9 GHz</td>
<td>14%(&gt;95%)</td>
<td>5.81 λ × 0.38 λ</td>
<td>high</td>
<td>difficult (bend waveguide)</td>
</tr>
<tr>
<td>[6]</td>
<td>N</td>
<td>Y</td>
<td>33 GHz</td>
<td>40.9%(&gt;97.7%)</td>
<td>1.56λ × 0.78 λ</td>
<td>low (corners)</td>
<td>difficult (twist waveguide)</td>
</tr>
<tr>
<td>[8]</td>
<td>Y</td>
<td>Y</td>
<td>8.5 GHz</td>
<td>12.8% (&gt;95%)</td>
<td>1.35 λ × 0.63 λ</td>
<td>high</td>
<td>difficult (bend waveguide)</td>
</tr>
<tr>
<td>[9]</td>
<td>Y</td>
<td>N</td>
<td>10 GHz</td>
<td>12%(&gt;99%)</td>
<td>1.25 λ × 1.1 λ</td>
<td>high</td>
<td>easy</td>
</tr>
<tr>
<td>[11]</td>
<td>N</td>
<td>N</td>
<td>10 GHz</td>
<td>17%(&gt;99%)</td>
<td>1.53 λ × 0.34 λ</td>
<td>low (bump element)</td>
<td>difficult (bump element)</td>
</tr>
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<td>[12]</td>
<td>Y</td>
<td>Y</td>
<td>15.1 GHz</td>
<td>13.2%(&gt;95%)</td>
<td>1.15λ × 0.51 λ</td>
<td>low (dielectric rods)</td>
<td>difficult (dielectric rods)</td>
</tr>
<tr>
<td>This work</td>
<td>Y</td>
<td>Y</td>
<td>9.5 GHz</td>
<td>4%(&gt;97.5%)</td>
<td>1.27 λ × 0.32 λ (Length:2.22λ)</td>
<td>high</td>
<td>easy</td>
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</table>

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References


