Compact Turnstile Quad-Ridge Orthomode Transducer with Octave Bandwidth for Radio Astronomy Applications

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ABSTRACT

A novel wideband orthomode transducer (OMT) featuring a folded-arm turnstile junction covering a 2:1 frequency band is employed to achieve an effective structure while meeting the strict OMT requirements for radio astronomy applications. The turnstile junction is designed with two symmetry planes to ensure separation between perpendicular polarizations and the effective management of higher order modes. Within the throat of the turnstile junction, stepped cylinders serve as scattering elements and matching stubs to ensure efficient impedance matching between the quad-ridge circular waveguide at the input and the single-ridge rectangular waveguides at the output. The folded arms play a pivotal role in achieving excellent matching while significantly reducing the overall size. Considering the significance of developing wideband radio astronomy receivers with minimal noise, this design demonstrates a precisely engineered compact OMT, with tuned bends, junctions, and delivers simulated return loss better than 20 dB while maintaining cross-polarization performance well below 65 dB within the specified 20-40 GHz frequency range.

Keywords: Ridged waveguide, compact turnstile junction, orthomode transducer (OMT), octave-band, polarization splitter, wideband receiver, ngVLA, ALMA, SKA, radio astronomy.

1. INTRODUCTION

Orthomode Transducers (OMTs) are complex electrical devices that feature four ports: two of these ports are connected to a single input waveguide, which is typically either square or circular in shape, while the other two are linked to standard rectangular waveguides that function as the primary output modes. This configuration allows the OMT to serve as a dual-mode passive component, effectively operating as a polarization diplexer. As such, OMTs play a crucial role in systems that need to manage and separate two orthogonal polarizations of electromagnetic waves. This capability ensures the simultaneous processing of different signal polarizations, improving signal integrity and reducing cross-polarization interference in applications such as telecommunications, radar systems, and radio telescopes. In the receiving mode, it separates two orthogonal linearly polarized signals from the shared waveguide into two outputs, while in the transmitting mode, it merges two distinct signals from separate outputs into the common input port [1]. OMTs are crucial components in antenna feeding systems spanning microwave, millimeter, and sub-millimeter wavelengths. Their ability enables feed horns, and consequently reflector antennas in radio astronomy, to operate with dual linear polarizations. Various symmetric [2] and asymmetric [3]OMT configurations are employed across various applications. In applications where phase difference, suppression of higher-order modes, and wider bandwidths are critical considerations, symmetric structures are generally favored for OMT designs. OMTs primarily fall into three distinct types: Boifot [4]turnstile junction[5], and Dunning[6]. Each of these designs offers unique advantages depending on their specific applications. The initial two waveguide configurations are recognized for their wide bandwidth, attributed to their symmetric structures. However, combining these arms adds complexity compared to the third category, which is better suited for narrower bandwidths. In situations where wide bandwidth is necessary, the inclusion of ridges becomes essential. When comparing turnstile OMTs with Boifot OMTs, the implementation process is comparatively simpler with turnstile OMTs [7]. In [8], a compact

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turnstile junction OMT operating in the W-band (75–110 GHz) and using a "swan neck" twist is introduced. The OMT was built by digital light processing (DLP) 3-D printing technology and despite achieving excellent outcomes in simulation, discrepancies in fabrication have led to a decline in both return loss (RL) and isolation. In [9], the turnstile OMT structure broadens operational bandwidth close to 2:1 frequency range through simple matching in rectangular waveguides and unique output waveguides. However, return loss remains around 10 dB at both frequency range boundaries, making it less ideal for radio astronomy applications which require better performance. [10] introduces two Ku-band OMTs. The initial design spans the frequency range of 10.4–18.8 GHz (57.5%) with a return loss of 24 dB. The second OMT, designed for the 12.60–18.25 GHz band, exhibits a measured return loss exceeding 29 dB within the specified band and an insertion loss of less than 0.11 dB for both polarizations. [11] describes a quad-ridge turnstile OMT designed for a frequency range of 24–51 GHz, spanning slightly more than an octave band. Notably, this design is tailored for radio astronomy applications and is fabricated using CNC machining across six layers.

The primary objective of this design is to develop an ortho-mode transducer that aligns with the specifications of the forthcoming Very Large Array (ngVLA) project managed by the National Radio Astronomy Observatory (NRAO). The aim is for this design to be considered a leading candidate for the next generation of wideband radio receivers [12]. There has been substantial research and development on various front-end components suitable for ngVLA Bands 3 to 6, as referenced in studies like [13], [14] and [15]. This design introduces a compact OMT that maintains robust performance capabilities, making it ideal for wideband front-end receivers, particularly for ngVLA Bands 4 or 5. It also offers scalability to other frequency bands, making it applicable for projects like SKA and ALMA. The model can be manufactured using CNC machining and, with careful planning, might also be adapted for 3D printing.

2. OMT DESIGN AND RESULTS

2.1 Quad-Ridge Waveguide Turnstile Junction

The most important element of the OMT is the input turnstile junction, which plays a critical role in dividing the incoming dual polarized receiving signals. The 3-D view and the inner ridge details of the folded turnstile junction are shown in Figure 1 (a). A 4.04 mm radius circular quad ridged waveguide input (Port 1) transitions to a (5.51×2.54 mm^2) single ridged rectangular waveguide through the four metallic matching elements which are placed at the junction for operating over a bandwidth from 20 GHz to 40 GHz with 20 dB return loss. The two orthogonal quasi-TE_{11} modes from the quad-ridged circular waveguide are split equally into two quasi-TE_{10} modes by the scattering element.

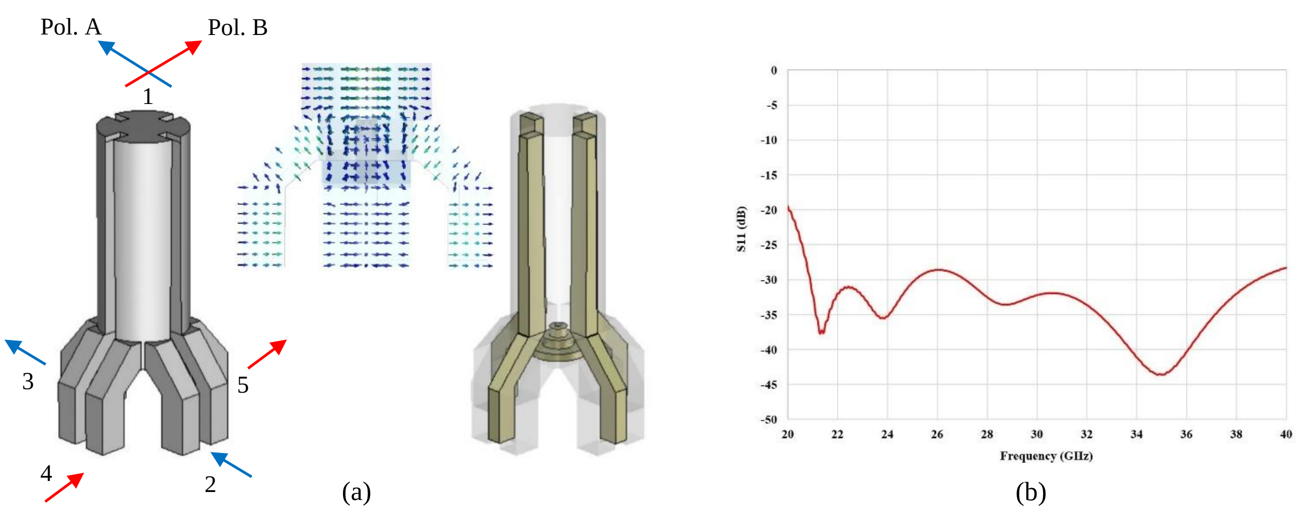

Figure 1. (a) CAD view depicts a turnstile junction with a quad-ridge waveguide input. In the visualization, the vacuum is represented by a transparent grey color, while the ridges are depicted as metal. The two linear polarizations, labeled as A and B, are indicated by blue and red arrows, respectively; (b) simulated reflection coefficient for the quad-ridge waveguide turnstile junction.

In the side view, the electric field line vectors are illustrated, indicating the division of the signal and the generation of opposite phases. The physical structures of the junction can create a discontinuity that excites higher order modes and leads to spikes in measurements. However, if the structure maintains symmetry in both the vertical (V) and horizontal (H) planes and avoids structural discontinuities, the excitation of most higher order modes can be suppressed, and the cross-polarization and isolation flattened out and improved considerably [16]. The folded arms offer a combined benefit of achieving good matching while significantly reducing the size. This reduction in size not only reduces mass in satellite systems but could enable the feeding of dense horn antenna arrays [3]. Figure 1(b) demonstrates the performance of the turnstile junction, which spans a frequency range of one octave. It maintains a reflection coefficient better than -27 dB for 90% of the band and exceeds -20 dB throughout the entire band.

2.2 E-Plane Bend and Y-Junction with Ridged Waveguides

The smallest cross-sectional area is achieved by employing simple E-plane bends with a 90-degree angle. The configuration and simulated reflection coefficient of the E-plane bend are shown in Figure 2 (a) which provides a return loss better than 36 dB across the bandwidth. To recombine the RF signals that are divided by the turnstile junction through the waveguide outputs in opposite directions, a power combiner with a 180˚ out-of-phase configuration is employed for each polarization. Furthermore, as the outputs require connection to a standard WRD180 ridged waveguide, the Y junction serves as a transition from the custom-designed ridged waveguide to WRD 180 ridged waveguide. Extending the Y junction helps reduce spikes and improve the return loss of the OMT, although a stepped junction can be employed to shorten it. Figure 2(b) displays the power combiner network along with its S_{11} parameter, presenting a return loss better than 28 dB.

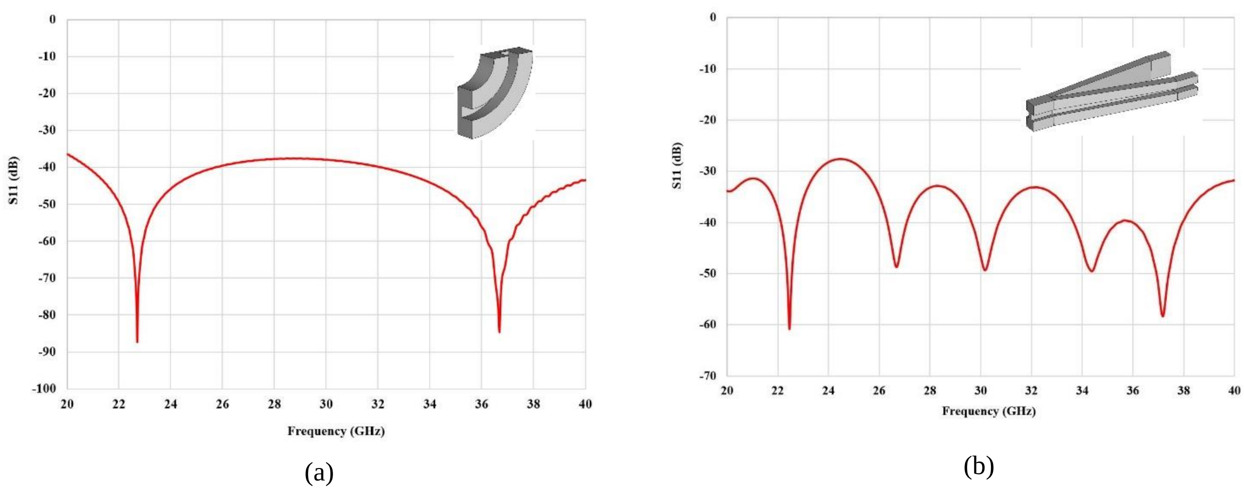

Figure 2. (a) CAD model showing the bend using a ridged waveguide and simulated reflection coefficient. (b) E-plane Y-junction and simulated input port reflection.

2.3 Design Overview of OMT

After designing the individual components of the OMT separately, the final optimization is conducted. The integration of bends and combiners is demonstrated in Figure 3, where they are incorporated into the OMT. Maintaining alignment, symmetry, and proper spacing is crucial to achieving a clean and optimal signal response. The proposed OMT was designed and simulated using two full wave electromagnetic simulators, µWave Wizard and CST Microwave Studio to confirm its functionality.

OMTs are often judged based on isolation and cross polarization between output ports. Dashed lines represent simulation results from µWaveWizard, while solid lines depict simulation results from CST. Figure 4 (a) displays the outcome of the complete OMT, illustrating its desired broad-frequency range capabilities. A reflection coefficient of -20 dB is predicted across the full octave band.

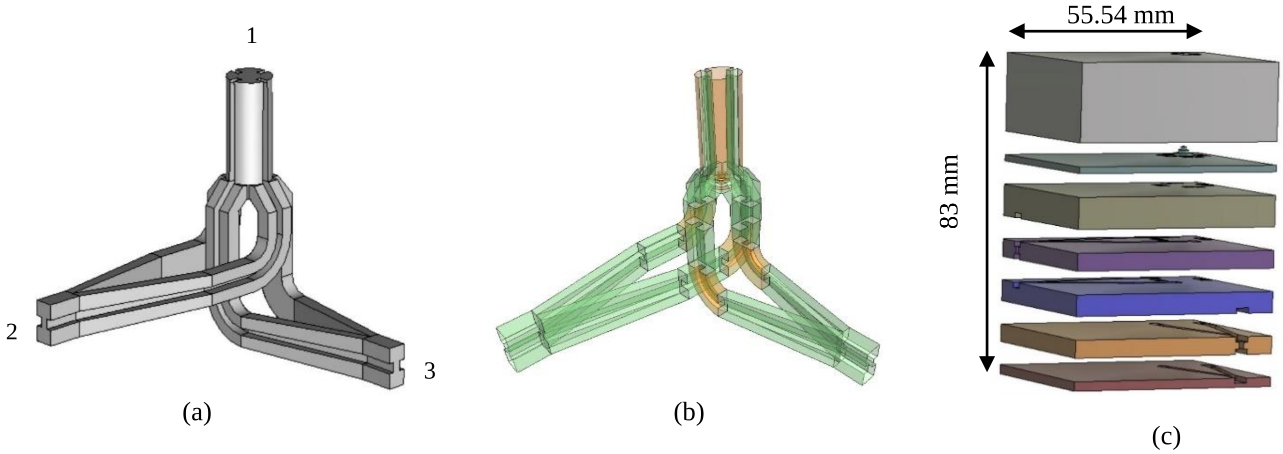

Figure 3. Internal view of the symmetric dual-side OMT, (a) in CST, (b) in µWaveWizard, (c) mechanical drawing for CNC machining.

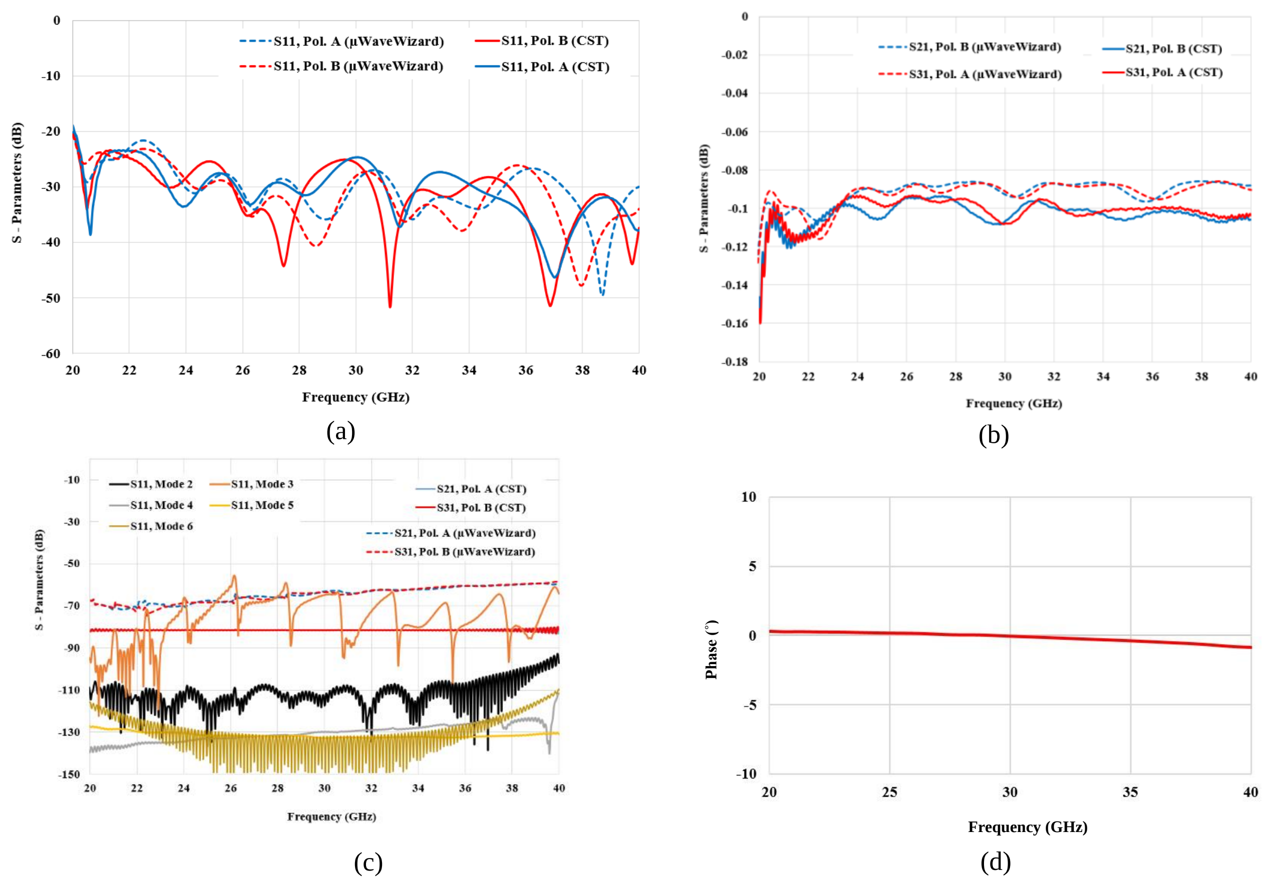

Figure 4. (a) Reflection coefficient, (b) insertion gain, (c) cross-polarization leakage and reflected higher-order modal conversion, (d) phase difference between each linear polarization.

Figure 4 (b) indicates around 0.1 dB simulated insertion loss across the band and in Figure 4 (c), the results indicate that the leakage of cross-polarization is below -65 dB, with a response suggesting minimal modal conversion and insignificant trapped energy within the structure. Additionally, the reflected higher-order modes are lower than -60 dB. The results of the simulated S parameters demonstrate consistent and satisfactory agreement between the two software tools throughout the entire frequency range of the octave band. The turnstile OMT has adopted layouts that achieve phase-matched outputs so that the phase difference between the two outputs is close to zero (Figure 4 (d)).

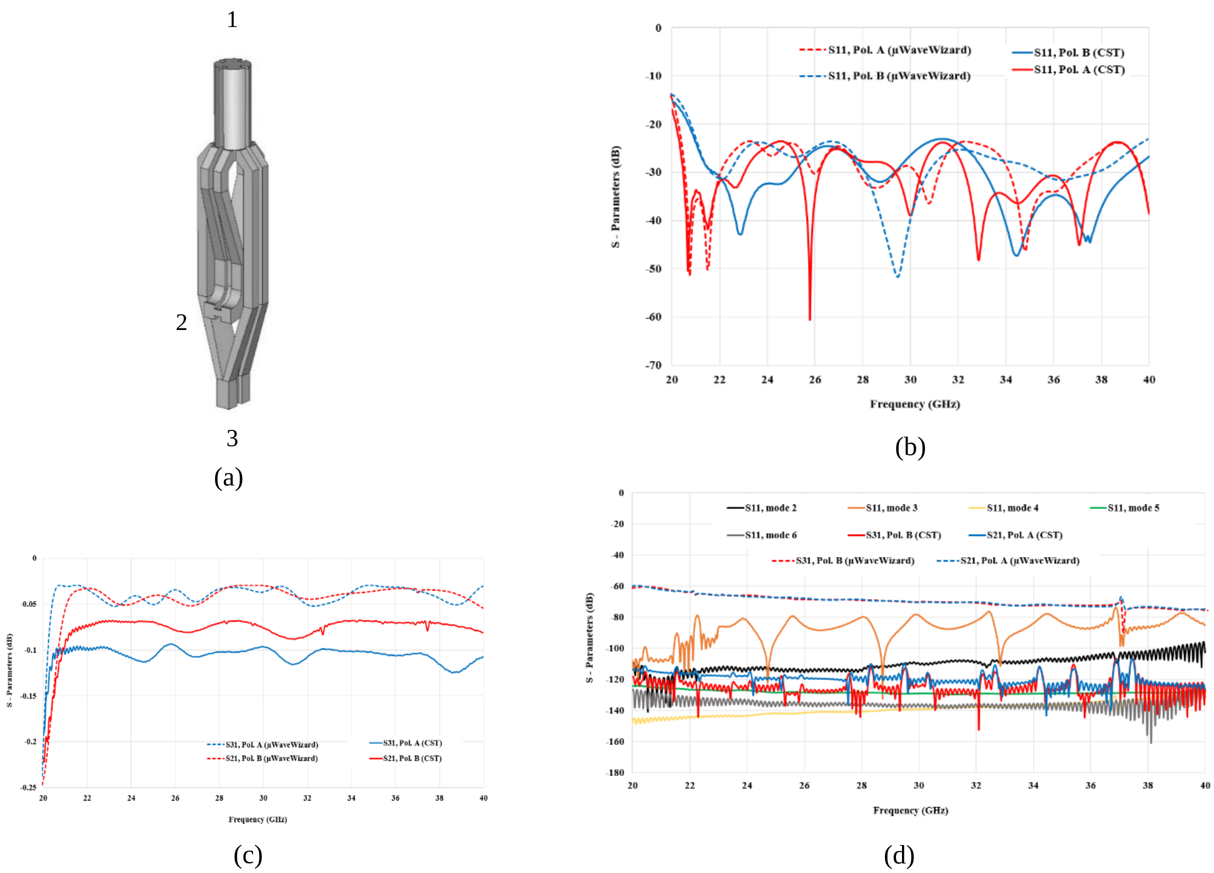

Figure 5. (a) An alternate OMT approach involving distinct combiner networks. (b) Reflection coefficient for two polarizations. (c) Insertion gains for two polarizations. (d) Cross-polarization leakage and reflected higher-order modal conversion.

Since linear polarization is commonly specified for various millimeter-wave radio astronomy applications, it is not necessary for the output branches of the OMT to be phase-matched. In these cases, the need for additional components such as a 90-degree hybrid or phase shifter is eliminated.

A second OMT design depicted in Figure 5(a) presents a more radially compact alternative configuration where the folded junction connects to various combiner networks. This design variant upholds nearly identical broadband requirements and demonstrates the adaptability of the newly introduced junction for effective routing and port positioning. The performance of this design, in terms of reflection coefficient, insertion loss, and cross polarization, is detailed in Figures 5(b), 5(c), and 5(d), respectively. Future work will involve evaluating the fabrication process and feasibility for each design.

3. CONCLUSION

An innovative method has been introduced to create an Orthomode Transducer (OMT) with octave-bandwidth capabilities. This approach utilizes ridged waveguides for wideband dual-polarization performance, which are then connected to a quad-ridge turnstile junction. This novel technique offers a significant advancement in the field of compact OMT design, providing enhanced performance across a wide frequency range. By incorporating ridged waveguides and a turnstile junction, this approach ensures efficient polarization separation while maintaining excellent broadband characteristics.

This design endeavors to attain desired outcomes through straightforward and condensed structures. Simulation results have effectively demonstrated its superior performance across an octave bandwidth ranging from 20 GHz to 40 GHz. These findings were validated through simulations conducted on two separate software platforms. The analysis revealed performance that would be suitable for a widened ngVLA Band 4 receiver.

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