Design of Reverse-Coupler Orthomode Transducer for 209-281 GHz

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***Abstract*— We describe the design of a waveguide orthomode transducer (OMT) for the 209–281 GHz frequency band. The device is one of three candidates being considered for deployment in the upgraded ALMA Band 6 receiver, called "Band 6v2," currently under development by NRAO. The OMT is based on a symmetric reverse coupler structure. It has a circular waveguide input port (diameter 1.29 mm) and two single-mode oval waveguide output ports with full-radius corners matched to WR3.7 rectangular waveguide (0.94×0.47 mm²). A circular-to-square waveguide transition is used on the input side. The two oval waveguide outputs have E-plane orientations parallel to each other and are located on opposite sides of the OMT module. A commercial 3D electro-magnetic simulator was used to optimize the design's performance.**

***Keywords*— Branch-line coupler, hybrid coupler, orthomode transducer, polarimetry, polarization splitter, power combiner, reverse coupler, waveguide transitions, radio astronomy.**

I. Introduction

An orthomode transducer is a passive device that separates two orthogonal linearly polarized signals propagating in a common circular or square waveguide into two independent single-mode output ports. Highly symmetric waveguide structures are required to avoid the excitation of higher-order modes in the common OMT waveguide input and to achieve a broad fractional frequency bandwidth (40% or wider). Since the small dimensions and tight tolerances pose a significant challenge for fabrication and assembly of the parts, only a few broadband OMT designs have been demonstrated to work well at mm- and sub-millimeter wavelengths [1-17].

The broadband Bøifot junction orthomode transducer [1] currently used in the ALMA Band 6 cartridges [2] utilizes a thin septum in the common waveguide arm and wires in the waveguide side-arms, whose positioning in the split-blocks is critical to performance, particularly to its polarization properties. As part of the ALMA Band 6v2 receiver upgrade project [18], NRAO is evaluating three types of OMT for the 209-281 GHz frequency band that do not use pins or septa: two double-ridge designs [12], including one from NAOJ [19], and a symmetric reverse-coupler design [20,21].

II. Specifications of Band 6v2 OMT

Due to the complexities of performing precise electrical measurements at cryogenic temperatures (4 K), the Band 6v2 OMT's electrical specifications, detailed in Table I, are to be met at room temperature (293 K). This requires accurate room-temperature testing of the device before its integration into the cryogenically cooled receiver where it will ultimately operate.

The Band 6v2 OMT is specifically designed to integrate with the ALMA Band 6v2 receiver system. At its input, a circular waveguide with a diameter of 1.29 mm ensures compatibility with the Band 6v2 feed horn. At its outputs, two oval waveguides (matching 0.94 x 0.47 mm² WR-3.7 rectangular waveguide) connect to the Band 6v2 sideband separating (2SB) SIS mixer modules [22, 23]. These outputs are positioned on opposite sides of the OMT module, with their E-planes (electric field polarization planes) parallel to each other to ease integration with the other receiver cartridge components. In the following section, we present the design of the NRAO symmetric reverse-coupler waveguide OMT for potential application in the Band 6v2 receiver cartridge.

TABLE I. Band 6v2 OMT electrical specifications to be met at room temperature, 293 K

Parameter	Specification
Frequency Band	209-281 GHz
Input Return Losses	≥15 dB
Output Return Losses	≥15 dB
Insertion Losses	≤0.5 dB
Isolation	≥30 dB
Cross-polarization	≥30 dB

III. Design of polarization-splitting symmetric reverse coupler waveguide structure

The symmetrical reverse-coupler waveguide structure illustrated in Fig. 1 is at the core of the broadband NRAO OMT candidate for Band 6v2. This design comprises four key elements:

a) Square waveguide input (0.94 x 0.94 mm²): This serves as the entry point for the incoming signal. Across the 209-281 GHz frequency range, it supports the two fundamental orthogonal modes TE_{10} (horizontal polarization, Pol 0) and TE_{01} (vertical polarization, Pol 1), as well as the higher order modes TE_{11} and TM_{11}, whose excitation is avoided by the twofold symmetry of the structure;
b) Two-section transformer for Pol 1: This component transitions the TE_{01} signal (vertical polarization) from the square waveguide to a rectangular waveguide (0.94 x 0.486 mm²), enabling efficient forward coupling;
c) Sidearm hybrid couplers: Two 90-degree hybrid waveguide couplers are positioned on the sidearms. These couplers split the incoming TE_{10} signal (horizontal polarization) into two equal outputs. The hybrids utilize branch-line coupling structures with four branches and reduced-height coupled waveguide (0.940×0.379 mm²). The separation between the main arm and the side arms (the width of the branch-lines) is 0.332 mm;
d) Reactively loaded terminations: Reactive terminations are placed at each hybrid coupler port. These terminations reflect the coupled Pol 0 signals back (reverse coupling) in anti-phase with equal power distribution (-3 dB).

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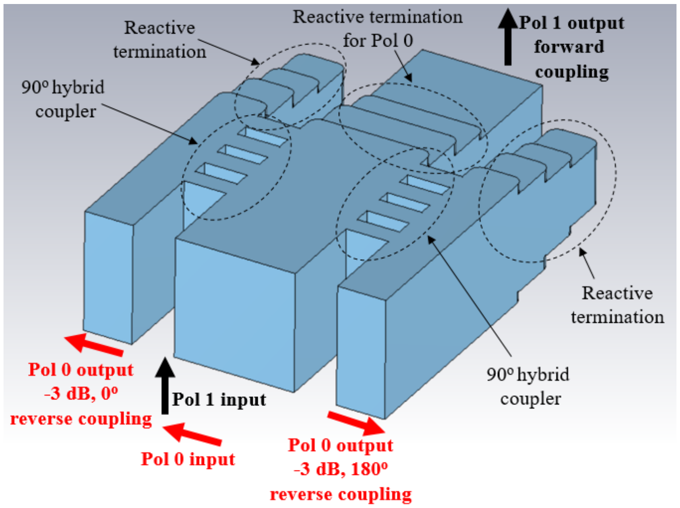

Fig. 1. Internal view of the symmetric dual-side backward coupler of our OMT with input square waveguide in common with two 3-dB branch-line coupling structures utilizing reactive terminations for Pol 0. The device has four physical ports and five electrical ports.

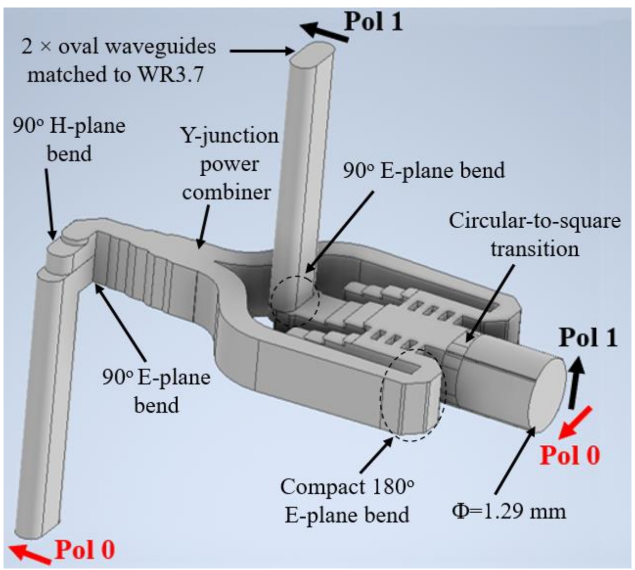

Fig. 2. Full OMT showing the circular waveguide input and the two oval waveguide outputs (matched to WR-3.7 waveguide).

IV. Complete Symmetric Reverse-Coupler OMT

While the previous section focused on the core functionality of the signal splitter (refer to Fig. 1), Figure 2 reveals the complete Band 6v2 OMT design. It includes various components working together to process the signals:

a) Quarter-wave circular-to-square waveguide transition: This section smoothly transforms the incoming signal from a circular waveguide (1.29 mm diameter, used for feed-horn compatibility) to the square waveguide (0.94 x 0.94 mm²) of the OMT reverse-coupler polarization-splitting structure. To minimize higher-order mode excitation caused by rotational misalignment, an OMT with a circular waveguide input is preferable to one with a square waveguide input. This approach contrasts with the Band 6v1 design, which features a circular-to-square waveguide transition within the feedhorn and a square waveguide interface, potentially increasing susceptibility to mode excitation due to misalignment;

b) Polarization-splitting structure: The symmetric branch-line coupling structure with reactive terminations, as explained earlier, separates the incoming horizontal polarization signal (Pol 0) and reflects it using branch lines and special terminations;

c) Pol 0 Signal Routing: Two compact 180° E-plane waveguide bends change the direction of the Pol 0 signal paths by 180 degrees within the plane of the electric field (E-plane), re-orienting them in the forward direction;

d) An E-plane 180° Y-junction combiner [24] merges the two separate Pol 0 signals into a single waveguide output;

e) 90° bends in the E-plane and H-plane: The cascade of these waveguide bends guides the signal through 90-degree turns in the designated planes to achieve the routing of Pol 0 to the OMT oval waveguide output. It is noted that the E-plane bend twists the polarization plane of Pol 0, achieving the desired orientation at the OMT output (this E-plane bend functionality is not required in the Bøifot OMT design used in ALMA Band 6v1. There, the Y-junction power combiner can be directly cascaded with a 90-degree H-plane bend due to a different requirement for the final E-plane orientation of the Pol 0 signal at the Bøifot OMT output);

f) A 90° waveguide bend in the E-plane cascaded to the forward-coupled port of the polarization-splitting structure routes the Pol 1 signal to the desired OMT oval waveguide output.

CST Studio Suite [25] was employed to perform electromagnetic field simulations and optimizations for the OMT design. Assuming perfectly aligned block halves and a conductivity of $\sigma = 2.23 \times 10^7$ S/m, simulations predict the complete structure (as shown in Fig. 2) will meet the specifications outlined in Table 1. Notably, simulated input and output reflections are below -20 dB, isolation is below -79 dB, cross-polarization is below -61 dB, and transmission surpasses -0.5 dB for both polarizations across the entire 209-281 GHz band. It's important to acknowledge that these exceptional isolation and cross-polarization values are predicted for an ideal OMT with perfect machining and alignment. Any misalignment of the block halves in a real-world OMT degrades this performance.

V. Conclusion

We presented the design of a symmetrical reverse-coupler orthomode transducer (OMT) for the 209-281 GHz frequency band, one among three candidate designs being considered for the ALMA Band 6v2 cryogenic receiver cartridge. The OMT successfully meets the electromagnetic requirements set for this application.

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