Highly-Balanced Quadrature Hybrid with 55% Bandwidth

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***Abstract*—A highly amplitude and phase balanced E-plane branch-line quadrature hybrid coupler is realized by using reduced-height, broaden width rectangular metallic waveguides and double-ridge waveguides structure. A design fit to the extended W-band frequency has been designed, fabricated and measured. The design criterion is set to amplitude imbalance < 1.0 dB and phase imbalance < 2 degrees. The simulated and measured results show frequency range over 67.31 – 117.5 GHz and 65.75 – 117.75 GHz fit to the design criterion, respectively. The matching and isolation are typically below -20 dB. A higher frequency version fit to the 125 – 220 GHz frequency range is also designed and now under fabricating and will be measured soon.**

***Keywords*—quadrature hybrid, E-plane branch-line coupler, rectangular waveguide, double-ridge waveguide.**

I. INTRODUCTION

THE requirement of the next generation instrumentation for radio astronomy push the development of the millimeter-wave components toward broader bandwidth. For frequency higher than 65GHz, precisely-machined waveguide components are still essential for very low-noise and very low-loss systems, especially for which operated in critical environment like cryogenically cooled receivers for millimeter-astronomy [1]. In this work, we try to push the fractional bandwidth of the 3-dB waveguide quadrature hybrid couplers as wide as possible. The possibility of using single- and double-ridge waveguide to enhance the bandwidth of quadrature hybrid with even better impedance matching, isolation, amplitude/phase balance is explored.

II. DESIGN CONSIDERATION

The demand of the ultrabroad bandwidth leads to the development of the ridge waveguide components, and a broadband 45 – 116 GHz ridge waveguide system has been demonstrated [2]. The previous work on the waveguide quadrature hybrid coupler to achieved over 50% bandwidth demonstrated that based on the rectangular waveguide, the bandwidth can be achieved but either the amplitude imbalance or the phase imbalance would be degraded, for example, the quadrature hybrid coupler based on the reduced height, broaden width rectangular waveguide can either achieve 1-dB amplitude imbalance but the phase difference within 90 +- 6 degrees, or 1.6-dB amplitude imbalance with 90 +- 1.5 degree phase imbalance [3]. If maintain the amplitude balance within +- 1dB, and keep the phase difference between through path and couple path within 90 +- 1.5 degrees, for 12^{th} order branch hybrid, the bandwidth is reduced to 44% [4].

The goal of this work is to seek for the E-plane quadrature hybrid 3-dB coupler design with ultra-broadband (BW >55%), low amplitude imbalance ($\Delta A < 1$ dB), low-phase imbalance ($\Delta\theta < 2$ degree), the input/output matchings and isolation better than -20 dB, and the design should be easily machined for mass production. Due to the fact that ridge waveguides are capable to provide 88.2% bandwidth [2], we try to utilize the ridge waveguides with as simple tee junction structures to form the branch waveguide coupler to fulfill the above requirement. The ridge waveguide provides the very broad bandwidth by reducing the guide wavelength dispersion. The tee junction in [5] is a good reference for broadband waveguide circuit design, but its structure is difficult unless using metallic 3-d printing techniques.

To enhance the fractional bandwidth wider than 50% and maintain both amplitude and phase balance in good performance, three different configurations of the E-plane 12^{th}-order branch-line quadrature hybrid coupler are explored: (i) single-ridge waveguides for main arms with rectangular waveguides for branches, (ii) single-ridge waveguides for main-arms with double-ridge waveguides for branches, and (iii) reduced height and broaden width rectangular waveguides for main arms with double-ridge waveguide for branches.

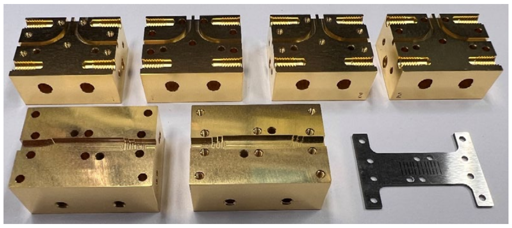
Among these three different configurations, case (i) is not possible to expand the bandwidth, its performance is very similar to the previous work shown in [3]. Both (ii) and (iii) is possible to achieve the fractional bandwidth up to 54%. However, for the 12-branch design, the branch waveguide height will be smaller for the configuration of case (ii) which is very difficult for fabrication and scale toward higher frequency. The design of case (iii) the bandwidth is slightly wider and the cross section of the branch waveguides is possible to be fabricated. The main-arm waveguide section between branches are fine-tuned to quarter wavelength of frequency cover the bandwidth as [4], and the length of the branch arms are all identical to quarter wavelength of around highest frequency, the aperture and cross section of the branch arms are also identical.

III. SIMULATION, FABRICATION, AND MEASURED RESULTS

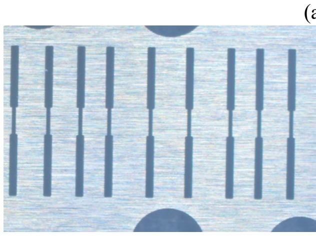
The simulation was realized by using the 3-dimensional EM structure simulator with time-domain finite-difference (FDTD) method and finite-element analysis method.

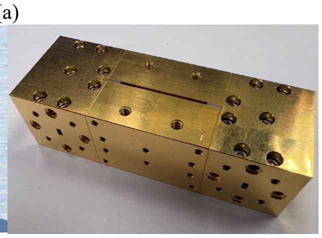
To ensure the fabricated hybrid coupler can be measured, additional waveguide section with transitions are extended from the intrinsic quadrature hybrid. The extended waveguide sections are in split-block design; thus, the full quadrature hybrid coupler is in 7-piece design, including 2 sets of split-block extended waveguide sections and the three-piece intrinsic quadrature hybrid (top main-arm waveguide, bottom main-arm waveguide, branch waveguide layer).

Even at extended W-band frequencies, the branch waveguide layer is still quite technical challenging on mechanical fabrication, several approaches are proposed for the fabrication, including the laser cutting, the wire cutting, and the dry-etching on the silicon substrate. The very high aspect ratio of the branch waveguide leads to the difficulty to be realized by dry etching, and the laser cutting could not produce the good ridge waveguide cross sections, thus the wire cutting is the only solution to produce the branch waveguide layer. Fig. 1 shows the mechanical fabrication of the branch waveguide layer.



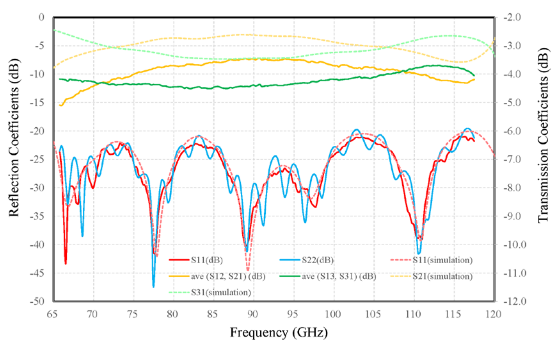
(a)



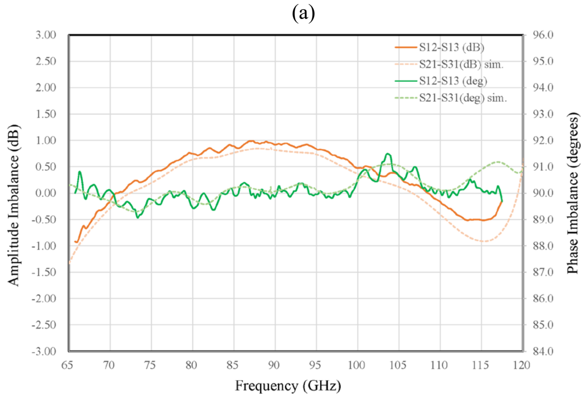


(b) (c)

Fig. 1 The mechanical fabrication of the branch waveguide quadrature hybrid, (a) individual components before assembling, (b) wire cutting result of the double-ridge waveguide branches, (c) assembled quadrature hybrid with the transition and taper waveguide sections to WR-10 flange.



(a)



(b)

Fig. 2. measured scattering parameters of the fabricated extended W-band quadrature hybrid coupler over 65.75 – 117.75 GHz, (a) coupled and through transmission coefficients, and reflection coefficient, (b amplitude and phase imbalance.

The measurement is realized by using the Keysight N5227B phasor network analyzer with N5292A millimeter-wave controller and a pair of WR-10 frequency extenders. By carefully setting to lower power level, the frequency range can be extended to 65.75 – 117.75 GHz, the upper frequency range is mainly limited by the TE_{01} mode of the WR-10 waveguide, which is 118GHz. The measured scattering parameters are presented in Fig. 2. Please noted that the gold-plating layer would leads to thickness change of the order of 1μm, which could help to maintain the amplitude and phase imbalance in the full waveguide band of 65.75 – 117.75 GHz within + - 1.00 dB and +1.0 / -1.5 degrees, respectively. The fractional bandwidth is 56.67%.

The design of the extended W-band quadrature hybrid is then scaled to shift the frequency range up to 125 – 220 GHz frequency by factor of 0.53 on mechanical size. The simulated performance and is as shown in Fig. 3

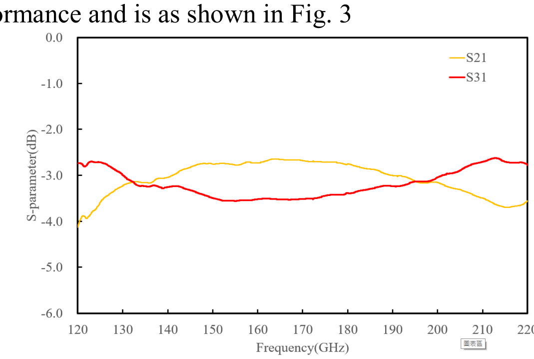


Fig. 3. simulated response of the 125 – 220 GHz branch waveguide quadrature hybrid.

TABLE I. PERFORMANCE SUMMARY†

Item	Simulation	Measured Result
Frequency (GHz)	66.5 – 119.5	65.75- 117.75
S_{21}, S_{31} (dB)	-3.7 to -2.5	-5.0 to -3.5
S_{11}, S_{22} (dB)	< -20.0	< -19.5
S_{41} (dB)	< -20.0	< -19.5
S_{21}/S_{31} (dB)	-1.0 to 0.85	-0.9 to 1.0
$\angle S_{21} - \angle S_{31}$ (deg.)	89.3 – 91.2	89 – 91.5

†Input: Port-1, Transmission: Port-2, Couple: Port-3, Isolation: Port-4 for future application to sideband separation down-converter.

IV. SUMMARY

An E-plane branch-line quadrature hybrid coupler with 55% bandwidth, <1.0-dB amplitude imbalance and < 2-degree phase error from 90 degrees is achieved. The higher frequency version for 125 – 220 GHz is now under fabrication for ALMA 2030 wideband sensitivity upgrade Band-4+5 prototype receivers.

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