Development of a Front End Array for Broadband Phased Array Receiver (Postprint)

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Abstract

The receiver is a signal receiving device located at the focal point of a telescope. To improve observation efficiency, the concept of the phased array receiver has been proposed in recent years, which involves placing a small phased array at the focal plane of the reflector, enabling flexible radiation pattern and beam scanning capabilities through a beamforming network. When combined with element multiplexing, all beams across the entire field of view can be observed simultaneously, achieving continuous sky coverage. This paper focuses on the front-end array of a phased array receiver operating at 0.7–1.8 GHz for the QiTai Telescope, and presents the design of a dual-linear-polarization Vivaldi antenna array with PCB structure. The antennas for each polarization are arranged in a rectangular grid of 11 × 10 elements. Based on focal field simulation results, 32, 18, and eight elements were selected to form a single beam at 0.7, 1.25, and 1.8 GHz, respectively. An analog beamforming network was implemented, with measured axial beam gains of 19.32, 13.72, and 15.22 dBi under uniform weighting. By combining the beam scanning method of reflector antennas, pattern tests were conducted on independent arrays with different element position sets required for PAF beam scanning. Pattern optimization at 1.25 GHz was performed using the conjugate field matching weighting method. Compared to uniform weighting, improvements were achieved in gain, sidelobe level, and main beam direction under conjugate field matching. Although there are slight differences between the test and simulation results, attributed to the passive array and laboratory testing conditions, this work has accumulated valuable experience in the development of front-end arrays for phased array receivers, and provides good guidance for future performance verification after the array is installed on the telescope.

Full Text

Preamble

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Development of a Front End Array for Broadband Phased Array Receiver

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Abstract

The receiver is a signal receiving device placed at the focus of the telescope. In order to improve the observation efficiency, the concept of phased array receiver has been proposed in recent years, which places a small phased array at the focal plane of the reflector, and flexible pattern and beam scanning functions can be achieved through a beamforming network. If combined with the element multiplexing, all beams within the entire field of view can be observed simultaneously to achieve continuous sky coverage. This article focuses on the front-end array of phased array receiver at 0.7–1.8 GHz for QiTai Telescope, and designs a Vivaldi antenna array of PCB structure with dual line polarization. Each polarization antenna is designed to arrange in a rectangle manner by 11 × 10. Based on the simulation results of the focal field, 32, 18, and eight elements were selected to form one beam at 0.7, 1.25, and 1.8 GHz. An analog beamforming network was constructed, and the measured gains of axial beam under uniform weighting were 19.32, 13.72, and 15.22 dBi. Combining the beam scanning method of reflector antenna, the pattern test of different position element sets required for PAF beam scanning was carried out under independent array. The pattern optimization at 1.25 GHz was carried out by weighting method of conjugate field matching.

Compared with uniform weighting, the gain, sidelobe level, and main beam direction under conjugate field matching have been improved. Although the above test and simulation results are slightly different, which is related to the passive array and laboratory testing condition, the relevant work has accumulated experience in the development of the front-end array for the phased array receiver, and has good guiding significance for future performance verification after the

array is installed on the telescope.

Key words: telescopes –instrumentation: detectors –techniques: radar astronomy

1. Introduction

A phased array receiver is a cutting-edge signal receiving technology in the field of radio astronomy in recent years. This technology arranges several electric small antenna units in a certain way at the focal plane of a radio telescope, and applies excitation to each array element through a beamforming network the amplitude and phase of each array element. Combined with the array element multiplexing function, multiple overlapping beams are formed instantaneously, achieving continuous field of view coverage and improving the efficiency of radio telescope sky survey (Wu 2013). Compared to traditional multi beam receiver, the front-end of a phased array receiver is more similar to a traditional phased array antenna. However, due to its placement in the focal plane of a radio telescope to replace the traditional feed, it is also called as Phased Array Feed (PAF) in the field of radio astronomy (Wu et al. 2013).

Many relevant research institutions internationally have conducted extensive theoretical research and engineering practice on PAF receiver. Currently, the main applications of PAF receiver to single aperture large radio telescopes include FLAG (Focal L band Array for GBT) assembled for GBT (Roshi et al. 2018) and AO19 cryo-PAF assembled for the former Arecibo telescope (Cortes-Medellin et al. 2015) in the United States, and the installation, debugging, and trial observation of the modified Mark II PAF were carried out on Parks in Australia (Chippendale et al. 2016) and Effelsberg in Germany (Deng et al. 2017), as shown in Figure 1 [Figure 1: see original paper].

The construction of the QiTai 110 m aperture radio telescope project of Xinjiang Astronomical Observatory (XAO), Chinese Academy of Sciences has started (Wang 2014), in which the planned 20 cm band (0.7–1.8 GHz) PAF is the only phased array receiver (Wang et al. 2023), and related technology research and development has been carried out. This article combines the technical requirements of the 20 cm band PAF receiver to design the front-end feed array, fabricate the prototype of antenna array, and conduct actual measurement and verification based on the conditions of the microwave technology laboratory of XAO.

2. Design of Front-End Array

2.1. Analysis of Focal Field

Since the PAF front-end array is placed on the focal plane of the reflector, in addition to considering the operational requirements for the data receiver, higher processing capabilities are also demanded from the digital backend. Therefore, when designing the PAF array, a trade-off in array size configuration is necessary.

2.2. Design of Array

In the basic design indicators of the array for 20 cm band PAF (Ma et al. 2019), in addition to the number of array elements in the order of 100, the array also needs to achieve a working bandwidth of 0.7-1.8 GHz, especially for the design of a 2.5 octave broadband array, the selection and layout of array elements are crucial.

2.2.1. Selection of Array Elements Figure 1 [Figure 1: see original paper] shows the Mark II PAF receiver installed on the Parkes 64 m telescope. When designing the array, it is also necessary to consider reflector parameters such as focal ratio and aperture, which would take considerable time to simulate across frequencies. Given that the energy distribution of the focal field is independent of the antenna aperture (He & Li 2013), and simulating the focal field of a 110 m aperture reflector would be computationally intensive, we employ a 4 m aperture reflector with a focal ratio of 0.33, consistent with the QiTai Telescope, for efficient focal field analysis and design.

First, the focal field size is set to 0.6 m × 0.6 m. Based on the 0.7-1.8 GHz operating frequency of the 20 cm band PAF, three representative frequency points—0.7, 1.25, and 1.8 GHz—were selected for focal field simulation. Figure 2 [Figure 2: see original paper] presents the simulation results of the normalized focal field at the three frequency points. The circular areas indicated by black lines represent the -3 dB and -10 dB edge taper regions after electric field normalization. As wavelength decreases, the edge taper area of the focal plane field also reduces. According to Tian (2023), at a focal ratio of 0.33, the -10 dB edge taper region captures approximately 70% of the energy. If the PAF array needs to capture more energy, it must extend beyond this region. For instance, the array could cover larger areas out to the first or third null depth (Tian et al. 2022), but this would simultaneously increase the array size, element count, overall weight, cost, and complexity of the cooling design.

Various antenna types are used in PAF arrays, including microstrip antennas (Hay et al. 2007), octagonal ring antennas (Zhang & Brown 2011), dipole antennas (Roshi et al. 2018), and Vivaldi antennas (Navarrini et al. 2018). Currently, Australia has developed a fully cooled PAF array for the Parkes 64 m radio telescope, utilizing a rocket-type antenna element—an optimized metallic Vivaldi antenna that achieves a 0.7-1.98 GHz operating bandwidth in array configuration (Dunning 2022). Considering the operating bandwidth of existing antennas and our requirement of 0.7-1.8 GHz, we selected the Vivaldi antenna as the array element due to its superior potential for broadband performance.

The Vivaldi antenna is a broadband slot antenna with an exponentially tapered profile, first proposed by Gibson in 1979. It couples energy to the antenna patch through microstrip transmission lines for radiation. When placed in an array configuration, Vivaldi antennas exhibit ultra-wideband performance. Theoretical analysis reveals that the operating principle of this ultra-wideband antenna array is similar to Munk' s strongly coupled dipole array, further validating the broadband Vivaldi antenna array theory based on enhanced coupling.

2.2.2. Layout of Array Based on the Vivaldi antenna selection and tightly coupled array arrangement design, and considering the dual linear polarization requirements, the Vivaldi antenna array is arranged in a rectangular grid. The elements are PCB-based Vivaldi antennas, with same-polarized antennas arranged in a 10 × 11 configuration.

This paper defines the two linear polarizations of the array as horizontal and vertical polarization. After multiple design iterations to optimize the Vivaldi antenna parameters, Figure 3 [Figure 3: see original paper] presents the simulated return loss for both polarized central elements under uniform array excitation. The results show that return loss remains below −10 dB across the 0.7–1.8 GHz operating bandwidth, demonstrating that the Vivaldi antenna array satisfies the bandwidth requirement.

The Vivaldi antenna array utilizes PCB material with a dielectric constant of 3.85 and thickness of 0.8 mm. Each individual Vivaldi antenna measures 30.025 mm in width and 161 mm in height, as shown in Figure 4 [Figure 4: see original paper]. To facilitate overall fabrication and assembly, the rectangular array is formed by cross-mounting two linearly polarized antenna arrays. Single-row antenna arrays with upward-opening slots are designated as horizontal polarization, while those with downward-opening slots are designated as vertical polarization, as illustrated in Figure 4 [Figure 4: see original paper]. This cross-mounted configuration of horizontal and vertical polarization arrays is shown in Figures 3 and 4 [Figure 3: see original paper][Figure 4: see original paper]. This design requires fabrication of only 22 antenna rows for complete array assembly (11 rows for each polarization), significantly reducing manufacturing costs.

Additionally, the optimized Vivaldi antenna features a conical open end with a width of 27 mm, a coupling slot line of 1.22 mm width, and a circular resonant cavity with a radius of 7.5248 mm to enhance antenna gain and pattern characteristics. A fan-shaped microstrip line of 9.5077 mm length improves port matching. Several through-holes with 0.25 mm radius are incorporated at the antenna' s radiating edge to optimize surface current distribution. The cross-mounting slot for a single antenna row has a height of 80 mm and width of 0.85 mm.

The complete single-row PCB measures 360 mm in width, accommodating 10 array elements plus outer edges, as depicted in Figure 5 [Figure 5: see original paper]. The fully assembled antenna array model is shown in Figure 6 [Figure 6: see original paper]. The overall array dimensions are 360 mm × 360 mm. When positioned at the reflector' s focal field, the array covers an area of 300.25 mm × 300.25 mm.

2.3. Design of Beam

Given the design challenge of achieving 0.7-1.8 GHz bandwidth and the constraint of approximately 100 elements, the final array size in the tightly coupled design is limited to 300 mm × 300 mm. This approach differs from array design sequences based on telescope field of view (Ma et al. 2021). However, since reflector testing conditions are currently unavailable, this design satisfies independent array performance requirements and enables measurement and verification in the XAO Microwave Technology Laboratory. Consequently, beam design is also based on this array model.

First, the fixed-size PAF array is positioned in the focal field at various parallel wave incidence angles to verify the focal field coverage range. Figure 7 [Figure 7: see original paper] illustrates the normalized -3 dB edge taper region and array coverage for axial incidence and off-axis incidence of one and two beamwidths on the reflector at 0.7 GHz. In the figure, the grid area represents the array, with horizontal and vertical lines denoting the horizontally and vertically polarized antenna arrays, respectively. The array fully covers the -3 dB edge taper region of the axial beam at 0.7 GHz. When the incident wave is offset by one beamwidth, the array covers only a small portion of the -3 dB edge taper region. At two beamwidths off-axis, the array no longer covers this region.

Figure 8 [Figure 8: see original paper] depicts the scenario at 1.25 GHz, where the array covers most of the -3 dB edge taper region when the incident wave is offset by one beamwidth. Figure 9 [Figure 9: see original paper] shows the 1.8 GHz case, where the array covers only a small portion of the -3 dB edge taper region when the incident wave is offset by two beamwidths.

Based on the focal field analysis above, our design utilizes only array elements within the -3 dB edge taper region to form a single beam. Figure 10 [Figure 10: see original paper] illustrates the relationship between the array and corresponding beams at the three frequency points. The black circular areas represent the -3 dB edge taper regions at each frequency, while the red grid indicates the array coverage. As shown, the Vivaldi antenna array can form only one beam at 0.7 GHz, four contiguous beams at 1.25 GHz, and nine contiguous beams at 1.8 GHz.

3. Development and Measurement of PAF Array Prototype

3.1. Development of Array

3.1.1. Fabrication of Array The Vivaldi antenna array employs a PCB structure using Rogers4003c substrate (dielectric constant of 3.38). Each row consists of 10 connected Vivaldi antenna units, with horizontal polarization antenna slots opening upward and vertical polarization slots opening downward, as shown in Figure 11 [Figure 11: see original paper]. The single-row horizontal and vertical polarized antennas are cross-assembled through upper and lower mounting slots, as illustrated in Figure 11 [Figure 11: see original paper]. Each polarization comprises 11 Vivaldi antenna rows, which are integrated into a complete antenna array through cross-assembly, also shown in Figure 11 [Figure 11: see original paper].

3.1.2. Assembly of Array The next step involves designing the array baseplate and mounting components. In addition to securing the entire Vivaldi antenna array, the assembly must accommodate soldering of 110 × 2 SMA connectors. A baseplate is designed for the array bottom, as shown in Figure 12 [Figure 12: see original paper]. One hundred through-holes are provided for installing adjacent pairs of SMA connectors for horizontal and vertical polarized Vivaldi antennas. These holes also allow a soldering iron to access the interior for welding antenna feed ports to SMA pins. A 2 mm deep groove is incorporated at the contact surface with the antenna array.

Long strip-shaped fixing clips (light blue components in Figure 12 [Figure 12: see original paper]) are designed on both sides of the baseplate along the vertical polarization direction to secure the nine rows of downward-slot antennas. Additionally, right-angle fixing clips at the four corners (light blue right-angle components in Figure 12 [Figure 12: see original paper]) anchor the edges of the two perpendicular antenna rows. The fabricated baseplate is shown in Figure 12 [Figure 12: see original paper].

Figure 13 [Figure 13: see original paper] displays top and bottom views of the array after installing the long strip fixing clips and baseplate. The baseplate securely positions the antenna array, though SMA connectors have not yet been installed in the through-holes. Following baseplate installation, 220 SMA connectors were installed and soldered, as shown in Figure 14 [Figure 14: see original paper]. To prevent performance degradation, a backplate was designed to cover the mounting holes at the array bottom, also shown in Figure 14 [Figure 14: see original paper]. This backplate features 220 through-holes to ensure unobstructed SMA connector access. The final assembled antenna array bottom view is presented in Figure 14 [Figure 14: see original paper].

3.2. Measurement of Array

3.2.1. Return Loss Due to the temporary unavailability of active array testing components, we conducted return loss measurements only on the passive array elements. Given the large number of elements, four representative positions in the vertical polarization were selected: N1,6, N1,11, N5,6, and N5,11. Figure 15 [Figure 15: see original paper] indicates these element positions on the array backplate, and also shows the return loss testing setup for element N5,6 using a vector network analyzer.

Figure 16 [Figure 16: see original paper] presents the passive return loss results for these four elements. While S11 remains below −10 dB at 1.25 GHz for each element, the −10 dB impedance bandwidth does not cover the full design bandwidth of 0.7-1.8 GHz. This discrepancy arises because simulations excite all array ports, enabling active elements to exhibit broadband characteristics through strong coupling effects, particularly for central array elements as shown in Figure 3 [Figure 3: see original paper]. In contrast, experimental measurements are performed on a passive array with all ports in a non-excited state, preventing the manifestation of broadband performance through strong coupling. Nevertheless, the measured passive return loss still reveals trends of the active array behavior. By adding matching loads to ports surrounding the test element, the −10 dB impedance bandwidth of central element N5,6 shows significant improvement over other elements, particularly achieving below −10 dB in the mid-to-high frequency range.

3.2.2. Pattern of Element Next, we measured the radiation patterns of individual elements in the passive array. A pattern measurement platform was constructed using an Agilent E8257D signal source (250 kHz–67 GHz) and an HD-0660DRHA10N double-ridged standard gain horn transmitting antenna (0.6-6 GHz). Power detection is performed using an Agilent U2004A power probe (9 kHz–6 GHz). As shown in Figure 17 [Figure 17: see original paper], the vertically polarized transmitting antenna on the left is positioned 3.2 m from the antenna array under test on the right, with the power probe connected to the vertically polarized element port. During measurement, the array antenna horizontally scans the transmitting antenna while the power probe collects data.

Figure 18 [Figure 18: see original paper] shows the measured pattern for vertically polarized central element N5,6 at 0.7, 1.25, and 1.8 GHz. During measurement, the signal source output power was set to 5 dBm, transmit antenna gain was 10.58 dB, cable and connector losses were 12 dB, and free-space path loss at 3.2 m distance was 39.5, 44.5, and 47.7 dB respectively (Wang & Xue 2013). The resulting measured gains were calculated as 2.62, 4.52, and 12.02 dBi. Figure 19 [Figure 19: see original paper] presents the corresponding simulation results for vertically polarized central element N5,6, with simulated gains of 6.18, 5.12, and 6.12 dBi respectively. Comparison reveals discrepancies between measured and simulated gains, most notably at 1.25 GHz where significant pattern center collapse occurs, resulting in sidelobe gains substantially higher than the central gain.

To comprehensively understand the behavior of each element and identify the cause of pattern center collapse at 1.25 GHz, we selected six elements from N5,1 to N5,6 along the horizontal direction and five elements from N1,6 to N5,6 along the vertical direction for comparative testing, leveraging the array’ s symmetry. The positions of these tested elements are shown in Figure 20 [Figure 20: see original paper].

Figure 21 [Figure 21: see original paper] presents the measured results for vertically polarized elements at 0.7 GHz. Figure 22 [Figure 22: see original paper] shows the corresponding simulation results for N5,6, N5,1, and N1,6 at 0.7 GHz. In the horizontal direction, as the measured element moves from center to left edge, measured gain increases and the pattern contour gradually develops a right-shifted bimodal characteristic. The measured gain of N5,1 is 5.32 dBi (simulated: 6.26 dBi). In the vertical direction, as the element moves from center to upper edge, measured gain decreases slightly with minimal pattern contour variation. The measured gain of N1,6 is 3.82 dBi (simulated: 5.76 dBi).

Figures 23 and 24 [Figure 23: see original paper][Figure 24: see original paper] present the measured and simulated pattern results at 1.25 GHz. In the horizontal direction, measured gain is slightly enhanced, with the pattern' s central contour gradually protruding and shifting rightward. The measured gain of N5,1 is 8.52 dBi (simulated: 5.21 dBi). In the vertical direction, measured gain increases significantly, and the pattern' s main lobe becomes more distinct. The measured gain of N1,6 is 12.62 dBi (simulated: 6.21 dBi).

Figures 25 and 26 [Figure 25: see original paper][Figure 26: see original paper] show the measured and simulated pattern results at 1.8 GHz. In the horizontal direction, measured gain change is not significant, and the pattern' s main lobe center shifts slightly rightward. The measured gain of N5,1 is 11.62 dBi (simulated: 7.23 dBi). In the vertical direction, measured gain variation is also minimal, with the pattern' s central contour gradually flattening. The measured gain of N1,6 is 12.22 dBi (simulated: 9.68 dBi).

3.2.3. Beamforming Following independent element testing, we utilized the available 32-channel power divider with the highest channel count (QPD32-700-2700-30-S, a 32-channel power divider from Qualwave Inc., 0.7–2.7 GHz) and selected 32, 18, and eight elements to form a single beam at 0.7, 1.25, and 1.8 GHz respectively, as shown in Figure 27 [Figure 27: see original paper]. The red markers indicate element positions for the axial beam at the three frequency points, while the yellow line denotes the −3 dB edge taper region of the focal field.

Since a reflector antenna is not available in the laboratory, the array cannot be positioned at the focal plane for practical PAF receiver measurements. Therefore, we performed analog beamforming tests and validation on the independent array using laboratory facilities. Beamforming employs uniform excitation with equal amplitude and phase. At 0.7, 1.25, and 1.8 GHz, 32, 18, and eight vertically polarized elements were selected respectively. Each element' s output port connects via a 1.5 m cable to the 32-channel power divider, whose combined output is then transmitted through another 1.5 m cable to the power probe for data collection. Figure 28 [Figure 28: see original paper] illustrates the analog beamforming network under uniform excitation at the three frequencies.

Using the same parameters as the independent element tests, but with cable and connector losses of 20 dB, the independent array pattern under equal amplitude-phase excitation at 0.7, 1.25, and 1.8 GHz is shown in Figure 29 [Figure 29: see original paper]. The measured gains were calculated as 19.32, 13.72, and 15.22 dBi respectively. Figure 30 [Figure 30: see original paper] presents the simulated beamforming pattern under uniform excitation, with gains of 6.64, 7.49, and 8.14 dBi. The measured results demonstrate that as the number of elements participating in beamforming increases, the measured gain improves significantly, while beamwidth decreases with increasing frequency. However, the 1.25 GHz measured beamforming pattern exhibits similar center collapse to that of the independent central element N5,6.

3.2.4. Beam Scanning As discussed in Section 2.3, the current array can achieve one-beamwidth scanning at 1.8 GHz. Referring to Figure 9 [Figure 9: see original paper], the −3 dB edge taper region of the focal field shows negligible change between axial and one-beamwidth off-axis beams at 1.8 GHz. Therefore, the number of array elements required to form any beam at a given frequency remains consistent across the array.

Considering that PAF beam scanning forms beams at different scan angles using elements within the corresponding focal field positions at various incident angles (as described in Section 2.3), and given the array layout, beams can be scanned by row, by column, or simultaneously by both. In Figure 31 [Figure 31: see original paper], yellow markers indicate the 32 elements for edge beam formation during D-axis scanning at 0.7 GHz, 18 elements for X-axis scanning at 1.25 GHz, and eight elements for Y-axis scanning at 1.8 GHz.

Figure 32 [Figure 32: see original paper] presents the measured patterns for the vertically polarized central axial beam and X-, Y-, and D-axis scanning beams at 0.7 GHz under uniform excitation. In the horizontal direction, as the 32-element set moves from center to left edge, the measured gains for scanning beams shifting two columns are 19.02 and 20.12 dBi. In the vertical direction, as the 32-element set moves from center to upper edge, the measured gain is 17.82 dBi. In the diagonal direction, as the set moves from center to upper-left edge, the measured gain is 18.42 dBi.

Figure 33 [Figure 33: see original paper] shows the measured patterns at 1.25 GHz. In the horizontal direction, as the 18-element set moves from center to left edge, the measured gains for scanning beams shifting three columns are 13.92, 14.72, and 15.62 dBi. In the vertical direction, as the set moves from center to upper edge, measured gains are 17.02 and 19.42 dBi. In the diagonal direction, moving from center to upper-left edge yields a measured gain of 19.62 dBi.

Figure 34 [Figure 34: see original paper] presents the measured patterns at 1.8 GHz. In the horizontal direction, as the eight-element set moves from center to left edge, measured gains are 13.82, 14.32, 14.72, and 15.72 dBi. In the vertical direction, moving from center to upper edge yields gains of 15.12, 14.52, and 14.82 dBi. In the diagonal direction, moving from center to upper-left edge produces gains of 16.12 and 16.52 dBi.

4. Discussion

Based on the measured patterns of independent elements and the array discussed above, the results reveal significant pattern defects in both the central element and array axial beam at 1.25 GHz, as evident in Figures 18 [Figure 18: see original paper] and 29 [Figure 29: see original paper]. Further analysis and discussion are warranted.

In Figure 23 [Figure 23: see original paper], as the measured element moves from center to left edge, test gain increases slightly, consistent with simulation trends. However, as the element moves from center to upper edge, test gain increases significantly, contrary to simulation results and trends.

Since the current array design is fixed and element characteristics cannot be altered, and considering that the PAF receiver will adjust the actual pattern through beamforming, we tested the pattern of the 18 elements forming the axial beam at 1.25 GHz under uniform excitation at the adjacent frequency of 1.3 GHz. Figure 35 [Figure 35: see original paper] shows these results. When the transmit signal shifts to 1.3 GHz, the pattern contour improves significantly —the collapsed region at 1.25 GHz shows substantial recovery, and the center exhibits a proper Gaussian distribution.

Since 1.25 GHz is the center frequency of the entire bandwidth and its performance is critical, we considered applying an appropriate weighting method to correct the concave pattern. The previously used uniform amplitude-phase excitation was adopted for implementation simplicity, but practical PAF receivers typically apply customized excitations. The conjugate field matching method is a fundamental beamforming algorithm for PAF receivers. Using 1.25 GHz focal field simulation results, we re-weighted the 18 elements, with the required amplitude and phase excitations for each array element to synthesize the central axial beam shown in Figure 36 [Figure 36: see original paper].

Figure 37 [Figure 37: see original paper] illustrates the analog beamforming network with amplitude-only and amplitude-phase adjustments based on conjugate field matching. Attenuators and phase shifters are employed for amplitude and phase control of the 18 elements.

Figure 38 [Figure 38: see original paper] presents the measured pattern of the central axial beam for the independent array under conjugate matching excitation (amplitude-only and amplitude-phase adjustment) at 1.25 GHz. Compared to uniform excitation, gain increases from 13.72 to 14.17 and 13.97 dBi, sidelobe level decreases from −0.21 to −2.74 and −3.08 dB, and main beam direction adjusts from 33° to 17° and −13°. These results demonstrate that conjugate matching excitation effectively improves sidelobe level and main beam direction at 1.25 GHz. We anticipate that more flexible digital beamforming methods and maximum signal-to-noise ratio beamforming algorithms could further optimize performance, which represents our future work.

5. Conclusion

This paper addresses the requirements for a phased array receiver in the 20 cm band of the XAO QiTai 110 m telescope, developing a broadband PAF receiver front-end array operating at 0.7-1.8 GHz. The array is a dual-linear-polarization PCB-based Vivaldi antenna array, with each polarization arranged in an 11 × 10 rectangular grid, measuring 360 mm × 360 mm overall. The design employs 32, 18, and eight elements within the −3 dB edge taper region of the focal field to form one beam at 0.7, 1.25, and 1.8 GHz respectively. Due to the temporary lack of relevant microwave components, this paper presents passive S-parameter and pattern performance tests conducted on the array using the XAO Microwave Technology Laboratory facilities. Test results show the array center element return loss is −12.5 dB at 1.25 GHz, and the measured axial beam gains under uniform analog beamforming excitation are 19.32 dBi at 0.7 GHz, 13.72 dBi at 1.25 GHz, and 15.22 dBi at 1.8 GHz.

Combining the PAF receiver' s beam scanning method in the reflector, pattern measurements of different array element sets required for PAF beam scanning were performed under independent array conditions. Additionally, addressing the concave contour issue of the 1.25 GHz central axial beam pattern under uniform excitation, conjugate matching excitation was applied for beamforming pattern tests at 1.25 GHz. After optimization, gain improved to 13.97 dBi, sidelobe level decreased to −3.08 dB, and main beam direction adjusted to −13°. Although discrepancies exist between test and simulation results due to array testing platform and laboratory environment conditions, the passive array work presented herein provides valuable experience for future more complex active array system integration. The implementation of this work has also enabled team members to further master phased array receiver and front-end feed array technology, providing good guidance for future performance verification after array installation on the reflector. Next, the project team needs to establish a complete phased array receiver, combined with a more comprehensive maximum signal-to-noise ratio beamforming algorithm and digital beamforming network to carry out related work, in order to better assist in the development of future 20 cm band PAF receiver.

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Note: Figure translations are in progress. See original paper for figures.