A Broadband Filter Transmitarray Based on Quasi-Yagi Antenna Element

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Abstract. A transmitarray (TA) antenna operating at X-band with band-pass filtering performance is presented. The proposed antenna is composed of a wideband TA and a filter feed antenna. Two quasi-Yagi antennas are connected as the unit cell of the proposed TA, leading to high transmission efficiency over a broadband range. By simply changing the length of the transmission lines, 360° phase shift is obtained. To verify this idea, a design with 16×26-unit cells is simulated and optimized, showing that approximately 14.5% 1-dB and 24.6% 3-dB gain bandwidths are achieved, respectively, with the peak gain of 23.1 dBi. Moreover, by employing the bandpass filter feed antenna, good bandpass filtering property is achieved, showing that the upper and lower out-of-band suppression in the 0.3GHz range can reach 27.3dB and 24.2dB, respectively, with the passband range from 9.6GHz to 11.9GHz.

1. Introduction

Recently, transmitarray antennas (TAs) have attracts huge research interests in academic and industry institute due to the low-cost, high-gain performance, easy beam forming and simple fabrication. Unlike traditional high-gain antenna array, which needs very complicated feed network, the TAs can avoid the use of feed network due to the space-fed technique. Meanwhile, compared to the reflectarray antennas (RAs), one advantage of TAs is that there are no blockage losses. A typical TA usually consists of a feed antenna and an array with high transmission efficiency. The electromagnetic (EM) waves produced by feed antenna illuminates the transmitarray. By properly adjusting the transmission phase on each unit cell, high-gain beam or other desired beams such as beam-scanning can be achieved. Two main approaches are proposed to design TAs so far. Employing frequency selective surfaces (FSSs) is the first method to design TAs. In this method, the unit cell of the TAs is designed using FSSs, acting as a space band-pass filter. By varying the physical dimension of array element, the corresponding transmission phase is changed as well. It should be noted that multi-layers of FSSs are necessary to achieve 360° phase shift, which increase the profile of the TAs. More importantly, the FSSs resonant frequency varies with the dimension change, leads to narrowing the transmission bandwidth. The other method to design TAs is based array antenna. In this method, two back-to-back antenna arrays are employed as receive side and transmit side. The receive side array receive the EM waves and then the transmit side array transmit EM waves. During this process, the transmission phase on each array element is adjusted to form desired radiation pattern. However, the TAs based on array antenna usually suffer from narrow bandwidth as well.

To improve the bandwidth of TAs, several researches have been carried out. For example, a photonic structure is applied in Ref. [1] as the unit cell of TAs, where a peak gain of 23 dBi with 5.7%...
1-dB bandwidth is obtained. In Ref. [2], four layer dual-ring slot unit cell is employed to design TAs. Using this structure achieves 7.4% 1-dB gain bandwidth. A four-layer TA with dual-square rings is proposed in Ref. [3], showing that the 1-dB gain bandwidth can reach to 7.5% with radiation efficiency of 47%. In Ref. [4], they reported a three-layer transmitarray antenna operating at 11.3 GHz with a maximum gain of 28.9 dBi, and a 1-dB bandwidth range of 9% and the aperture efficiency of 30%. In Ref. [5], an antenna operating at 13.5 GHz is proposed. The reported antenna has 30.22 dBi peak gain, 9.8% 1-dB gain bandwidth and 50% radiation efficiency, respectively. In current years, many researches are focus on broadband performance of the transmission arrays, and there are almost no research concentrates on the wideband filtering characteristics. Therefore, this paper will explore the broadband filtering characteristics of the transmitarray based on the broadband characteristics.

A high-gain wideband TAs based on array antenna is proposed in this paper. Broadband quasi-Yagi antenna is applied as the basic structure of TAs unit cell, where two quasi-Yagi antennas are connected back-to-back. High transmission efficiency of the unit cell is achieved over a wideband range due to the broadband impedance matching of the unit cell. A TAs operating at X band is designed, simulated and optimized. The proposed design has the peak gain of 23.1 dBi. Meanwhile, this design obtains 15.4% 1-dB gain bandwidth and 24.6% 3-dB gain bandwidth, respectively. To integrate filtering property, a filter feed antenna is employed as well. By using the filter feed antenna, the maximum gain is changed to 22.2dB with good bandpass characteristics.

2. Design of Unit Cell and Bandpass Filter Feed

Figure 1 shows the structure of a quasi-Yagi antenna [6]. As can be seen, the quasi-Yagi antenna consists of a half-wave driven dipole, a director and ground plane. On the top side of the substrate, there are reflector, right driven arm and the feeding line. The other driven arm and ground plane are etched on the bottom side of the substrate. Impedance matching technique is used to obtain wideband performance. Figure 2a shows the simulated S parameters of the proposed quasi-Yagi antenna. As can be seen, in the frequency range from 8.2 GHz to 12.5 GHz, the quasi-Yagi antenna works well with 43% bandwidth. Figure 2b shows the radiation patterns at phi=0° plane and phi=90° plane, respectively. In this design, 0.8mm Rogers 4003 C ($\varepsilon_r$=3.55) is selected as the substrate. Table 1 list

| Parameter | Value | Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|-----------|-------|
| A         | 30    | E         | 15    | L₂        | 7.5   | W₃        | 5.37  |
| B         | 15    | L₁        | 15    | W₂        | 1.2   | L₄        | 0.6   |
| C         | 1.98  | W₁        | 0.5   | L₃        | 0.85  | W₄        | 7     |

**Table 1.** Optimized parameters of the quasi-Yagi antenna. (unit: mm).
Figure 3 shows the configuration of the proposed unit cell. It can be seen that two quasi-Yagi antennas are connected acting as receive-side and transmit-side. The EM waves is received from the receive-side quasi-Yagi antenna and the transmitted through the transmit-side quasi-Yagi antenna. During this process, by changing the transmission lines length, the corresponding transmission phase is changed. It should be noted that the changing transmission length has little influence on the transition magnitude, which keeps a high transmission efficiency for the whole unit cell of the TAs. The proposed unit cell is simulated using commercial software HFSS. During the simulation, the periodic boundary is considered as well. Figure 4a plots the simulated transmission coefficient. As can be seen, the proposed unit cell can keep transmission magnitude higher than -1.5 dB in the frequency range of 9.5 GHz to 12.6 GHz. The phase shift with different L is plotted in figure 4b, where 360° phase shift is obtained when L varies from 0 mm to 15 mm. It also can be observed that the phase shift curves at different frequencies are almost parallel, which means the proposed unit cell has broadband property.

![Figure 3](image1.png)  ![Figure 4](image2.png)

**Figure 3.** The structure of the unit cell: (a) top side view; (b) bottom side view.

**Figure 4.** The simulated result: (a) the transmission magnitude (b) the transmission phase at different frequencies.

After the design of the broadband transmission unit is completed, the feed of the bandpass filtering characteristics will be designed. This bandpass filter feed is extended on the basis of the original quasi-Yagi antenna, as long as the filtering part is added to the original quasi-Yagi antenna. The filtering part of the feed is shown in figure 5a, the basic structure is a microstrip antenna. The material of the dielectric substrate is Rogers 4003C too, the microstrip antenna is between the metal patch and the ground plate, after being fed there is a potential difference, so a distributed electric field will be generated around the electromagnetic field, then the electricity and magnetic will transform into each other. The filtering part will replace the initial feeding line with a cascaded microstrip line, and the gap between each microstrip lines will cuts off the original current distribution then electricity and magnetic would coupling, so the antenna has a characteristic of bandpass filtering, figure 5b shows the simulated S parameter of the filtering part.

It can be seen that the transmission curve of the filtering part is great, the magnitude of S21 can reach about -0.8dB from 9.9GHz to 12.1GHz, and the magnitude of the corresponding S11 parameter is close to -20dB, demonstrating favourable band-pass filtering performance.

Connecting the filtering part to the feeding line of the quasi-Yagi antenna will form a feed with band-pass filtering characteristics. Figures 6a and 6b show the structure and simulation data of the bandpass filter feed, respectively. As shown in figure 6b, the simulated S11 parameters of the filter feed from 9.5GHz to 11.6GHz are below -10dB, while the S11 parameters before 9.2GHz and after 11.9GHz are above -2dB, which has the effect of steep drop.
To form a convergency beam pointing at broadside [7-9], the corresponding phase distribution can be obtained by the equation

\[
\phi = \frac{1}{2} \left\{ \frac{2\pi}{k} \left( \sqrt{(x_i - x_f)^2 + (y_j - y_f)^2 + (z_f^2 - z_j)} \right) \right\}
\]

where \((x_f, y_f, z_f)\) is the position of the feed antenna, \((x_i, y_i)\) is the position of the unit cell on the TA. In this equation, the TAs is assumed to be placed on \(z=0\) plane.

### 3. Transmitarray Design and Simulation Results

Before verifying the wideband filtering characteristics of the transmission array, the broadband characteristics of the array need be researched firstly and the best gain bandwidth should be found. A general end-fire feed antenna is needed to be mounted in front of the array when studying the broadband characteristics. For simplicity, the quasi-Yagi antenna shown in figure 1 can be used at this time.

To validate the design, a broadband TA antenna operating at the centre frequency of 11 GHz is designed. The antenna performance bases on different focal diameter ratio is discussed in figure 7. As shown in figure 7a, the peak gain increases with the growth of aperture dimension. When the aperture dimension is 300 mm, the gain reaches to 24.25 dBi. While, the 1-dB and 3-dB gain bandwidths are not linear to the aperture dimension. Compared to other two cases, the aperture dimension of 240 mm is more desirable, whose 1-dB gain bandwidth reaches to 11.36% and the 3-dB gain bandwidth reaches to 19.09%, respectively.

The impact of focal length (F) on antenna gain bandwidth is presented in figure 7b, where three focal lengths are studied with fixed aperture size (D=240 mm). When F increases from 144 mm to 168mm, the maximum gain increases from 22.68 dBi to 23.1 dBi. Meanwhile, the 1-dB gain bandwidth and 3-dB gain bandwidth grow up to 14.5% and 24.6%, respectively. However, when F keeps increasing, both of the maximum gain and gain bandwidth show a downward trend. This is because when focal length increases enough, the RF energy can’t be received and transmitted by the transmitarray effectively, resulting in lower maximum gain and narrower gain bandwidth [9-10].

Considering the performance of gain and gain bandwidth, 240 mm aperture dimension with 168 mm focal length is selected, and unit cells’ number is 16×26. The phase distribution and corresponding transmitarray are shown in figure 8.

On the basis of broadband performance, the research of wideband filtering characteristics can be carried out. At this moment, the array structure has been fixed. To study the filtering characteristics, it is necessary to replace the original end-fire quasi-Yagi antenna feed with a bandpass filter feed shown in figure 6a. The bandpass filter feed is placed in front of the broadband array according to the focal length, the results of broadband performance and wideband filter performance are exhibited in figures 9a and 9b, respectively.
Figure 7. (a) The TAs bandwidth with different D; (b) the TAs bandwidth with different F.

The simulated results of the proposed filter transmitarray is shown in figure 9b. The maximum gain of the transmitarray is 22.2dBi, and the 3-dB side frequency points are 9.6GHz and 11.9GHz respectively. For the left frequency point, the out-of-band suppression can reach about 24.2dB within 0.3GHz. For the right frequency point, the out-of-band suppression within 0.35GHz range can reach 27.3dB. The simulated result compared with the broadband performance shows that its bandpass filtering characteristics are good. And the radiation pattern of each frequency point is shown in figures 10-12.

Figure 9. The simulated result of the transmitarray: (a) the broadband TA; (b) the filter TA.

Figure 10. The radiation pattern the wideband filter transmitarray (within the bandpass): (a) 10.5GHz; (b) 11GHz.

Figure 11. The radiation pattern the wideband filter transmitarray (at the out-of-side frequency points): (a) 9.6GHz; (b) 11.9GHz.

Figure 12. The radiation pattern the wideband filter transmitarray (beyond the bandpass): (a) 9.5GHz; (b) 12GHz.

In the figure of radiation pattern, figures 10a and 10b are the frequency points in the bandpass, and the E-plane and the H-plane have a high degree of coincidence which shows the radiation pattern is great. Figures 11a and 11b are the results at the lower and upper out-of-side frequency points, the
corresponding gain differs from the highest gain by 3-dB, and the agreement between the E-plane and H-plane is not as high as figures 10a and 10b which within the bandpass range, but the radiation pattern is also good. Figures 12a and 12b are the radiation patterns at the frequency of 0.1GHz from the lower and upper out-of-side frequency points, it can be seen that the compatibility between the E-plane and the H-plane has deviated, and the radiation pattern changes in the direction of the bad, which is mainly due to the out-of-band suppression characteristic of the bandpass filter. The radiation pattern diagrams of these frequency points also corroborate the gain bandwidth diagram, indicating that the transmitarray has good bandpass filtering characteristics.

4. Conclusion
The paper proposes a transmitarray operating at X-band with a center frequency of 11 GHz. By changing the length of the transmission line, the corresponding transmission phase can be easily changed. A TA with the proposed unit cell is designed, simulated and optimized. Simulated results show that the peak gain of 23.1 dB is obtained. More importantly, the antenna gain bandwidth improves significantly using the proposed unit cell, whose 1-dB gain bandwidth and 3-dB gain bandwidth reaches to 14.5% and 24.6%, respectively. After a bandpass filtering feed is placed on the wideband array, the transmitarray provides bandpass filtering characteristics. The final simulation results show that the passband of the transmitarray range is 9.6GHz to 11.9GHz, and the upper and lower out-of-band suppression in the 0.3GHz range can reach 27.3dB and 24.2dB, respectively.

References
[1] Rahmati B and Hassani H R 2015 Low-profile slot transmitarray antenna IEEE Transactions on Antennas and Propagation 63 174-81.
[2] Liu G, Wang H j, Jiang J S, Xue F and Yi M 2015 A high-efficiency transmitarray antenna using double split ring slot elements IEEE Antennas and Wireless Propagation Letters 14 1415-8.
[3] Ryan C G M, Chaharmir M R, Shaker J, Bray J R, Antar Y M M and Ittipiboon A 2010 A wideband transmitarray using dual-resonant double square rings IEEE Transactions on Antennas and Propagation 58 1486-93.
[4] Abdelrahman A H, Elsherbeni A Z and Yang F 2014 High gain and broadband transmitarray antenna using triple-layer spiral dipole elements IEEE Antennas and Wireless Propagation Letters 13 1288-91.
[5] Abdelrahman H, Nayeri P, Elsherbeni A Z and Yang F 2015 Bandwidth improvement methods of transmitarray antennas IEEE Transactions on Antennas and Propagation 63 2946-54.
[6] Guiping Z, et al 2003 Simplified feeding for a modified printed Yagi antenna IEEE Antennas and Propagation Society International Symposium 3 934-7.
[7] Tian C, Jiao Y, Zhao G and Wang H 2017 A wideband transmitarray using triple-layer elements combined with cross slots and double square rings IEEE Antennas and Wireless Propagation Letters 16 1561-4.
[8] Luo Q, Gao S, Sobhy M and Yang X 2018 Wideband transmitarray with reduced profile IEEE Antennas & Wireless Propagation Letters 17 450-3.
[9] Ramazannia Tuloti S H, Rezaei P, and Hamedani F T 2018 High-efficient wideband transmitarray antenna IEEE Antennas & Wireless Propagation Letters 17 817-20.
[10] Di Palma L, Clemente A, Dussopt L, Sauleau R, Potier P and Poulguen P 2015 Circularly polarized transmitarray with sequential rotation in Ka-band IEEE Transactions on Antennas and Propagation 63 5118-24.