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A Wideband Transmitarray Using Double-Petal Loop Elements

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Abstract—In this letter, a four-layer transmitarray operating at 9.5 GHz is designed using a double-petal loop element as the unit cell. A configuration of the double-petal loop elements is used to increase transmission phase variation while maintaining a wide transmission magnitude bandwidth of the unit cell, and a full transmission phase range of 360° is achieved for a transmission magnitude equals to or better than −2.4 dB. Furthermore, the oblique performance of the unit cell is also good. Then, a prime-focus 676-element microstrip transmitarray with the proposed element is fabricated and measured. The highest measured gain is about 22.15 dBi at 9.8 GHz, resulting in a 31% aperture efficiency. The antenna bandwidth of 10.2% (from 9.3 to 10.3 GHz) for 1-dB gain is achieved in this design.

1. INTRODUCTION

The microstrip transmitarray is rapidly used in both terrestrial and satellite communication systems because of its advantages such as high gain, low mass and volume, inexpensive manufacture, and no insertion loss of a phased array's feed network at millimeter wave frequencies [1–4]. Due to the planar array of printed patch elements, the transmitarray avoids the fabrication complexity inherent in lens antenna. Furthermore, the feed can be placed directly in front of the aperture without incurring the blockage losses of a reflectarray configuration, which usually results in high aperture efficiency [5, 6].

The two most important design criteria for a transmitarray element are its phase range and transmission magnitude. Firstly, in order for an element design to be suitable for a large array where there is possibly phase shifting range in the aperture fields, a phase tuning range of 360° is required. Secondly, the transmission magnitude needs to be close to 1 (0 dB) to ensure a high aperture efficiency. Thus, the design process must involve both the transmission phase shift and magnitude of the element. In addition, the severe drawback of the microstrip transmitarray is its limited bandwidth performance, which is usually 7% or less, and intense efforts have been made in recent years to overcome this shortcoming [1, 4, 5, 7] and [8]. In this paper, we present a novel transmitarray operating at 9.5 GHz which uses a double-petal loop as the unit cell element and offers a wider bandwidth than previously achieved ones.

To date, in order to obtain a transmission phase range of 360°, while maintaining the high value of the transmission magnitude, there are many different techniques to control the transmission coefficient of each unit cell in the array. One approach involves using multilayer frequency selective surfaces [1, 5, 6] and [9]. This approach is popularly used to control the transmission magnitude and phase of each element in the array individually by varying the element dimensions. In [1], a four-layer double square ring transmitarray element, operating at 30 GHz, is designed to achieve the required transmission phase range of 360°. A triple-layer transmitarray antenna is designed in [6], which achieves high gain of 28.9 dB at 11.3 GHz and bandwidths of 9% for 1-dB gain. Another approach is receiver-transmitter designs [10–13]. In this approach, a transmitarray antenna typically consists of two planar arrays of

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printed-type elements. One of the arrays acts as a receiver, and it is illuminated by the antenna feed source. The other array radiates into free space, and it acts as a transmitter. A coupling structure is designed between the two arrays to attain a specific phase and magnitude distribution. In [10], a planar lens antenna based on aperture coupled microstrip patch elements with stripline delay lines is presented. It is worthwhile to point out that these techniques mostly use printed-type elements mounted on substrate materials. The third approach to control the element phase is to vary the effective substrate permittivity and permeability using metamaterial configuration [14, 15].

A double-petal loop element is proposed in this letter to design a four-layer transmitarray antenna. The measured gain of the transmitarray prototype is 22.15 dBi at 9.5 GHz, and the aperture efficiency is 31%. The measured 1-dB gain bandwidth is 10.2%, which is considered broadband performance compared with the published designs in [1, 4–8].

2. DOUBLE-PETAL LOOP TRANSMITARRAY ANTENNA DESIGN

A double-petal loop element shown in Figure 1 is simulated using Ansoft HFSS ver. 15. The phasing elements operate around resonance with unit cell periodicity of $P = 15\,\text{mm} \approx 0.5\lambda$. Here, λ stands for the free-space wavelength at the center frequency of 9.5 GHz. Periodic boundary conditions are introduced to take into account interactions with identical neighbor elements. The double-petal loop element is printed on a substrate with a relative permittivity of $\varepsilon_r = 2.65$. The substrate is suspended above ground plane with a distance of $h_1 = 8\,\text{mm}$, which is equal to $\lambda/4$. This configuration illustrates that a unit cell of four identical conductor layers, separated by quarter wavelength air gaps, can achieve a full transmission phase range of 360° where the transmission magnitude is better than −2.4 dB. The relation of L_1 and L_2 is assumed as $L_2 = L_1 \times K$ $(0 < K < 1)$. To validate the proposed design and evaluate its magnitude and phase as well as bandwidth performances, a parametric study is carried out for variations of W and K.

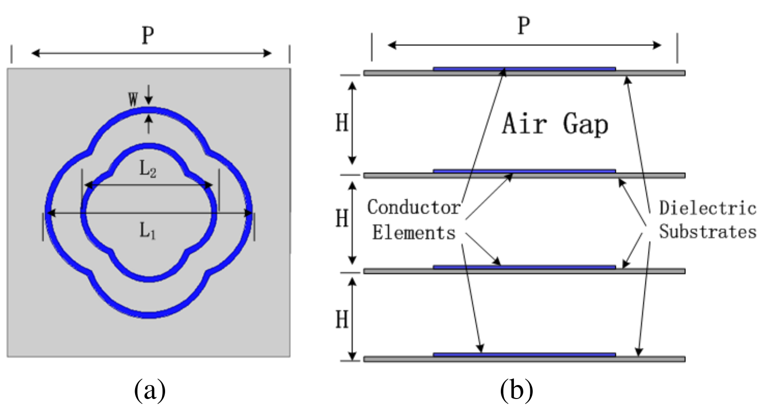


Figure 1. Geometry of the proposed element. (a) Top view and (b) side view.

Figure 2 shows the transmission magnitude and phase versus the length L_1 at the center frequency of 9.5 GHz, which confirms the characteristic of 360° transmission phase range with transmission magnitude better than −2.4 dB. Furthermore, a 300° phase range is achieved with magnitude better than −1 dB.

Figure 3 shows the influences of W on the transmission coefficient of the proposed unit cell at the center frequency of 9.5 GHz. It can be concluded that width W can have a great influence on both transmission magnitude and phase. When W is equal to 0.2 mm and 0.5 mm, the phase ranges are respectively 350° and 360° with magnitude better than −3 dB for the proposed structure. Furthermore, when W is equal to 0.3 mm, there are better linear transmission phase and magnitude for the proposed structure with L_1 varying from 5 to 10 mm. It can also make the design less sensitive to manufacturing error.

Figure 4 presents the influences of the variation of K on the transmission coefficient of the proposed unit cell. It can be concluded from Figure 4 that factor K has significant influence on both the

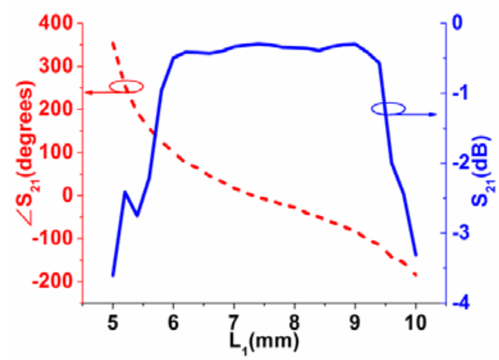
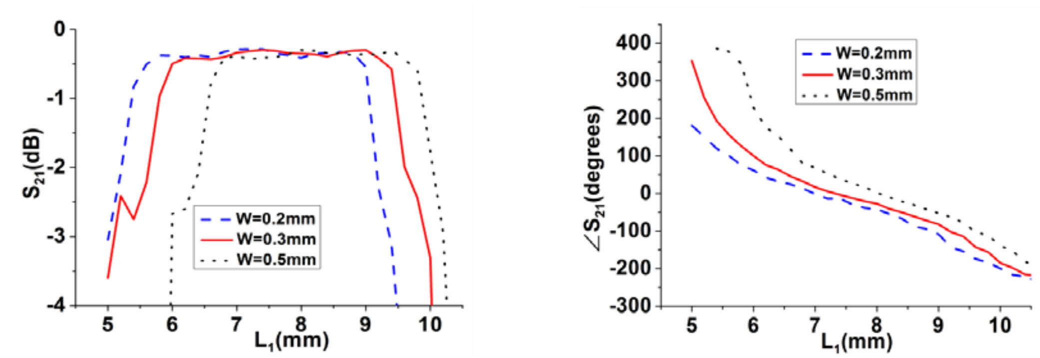
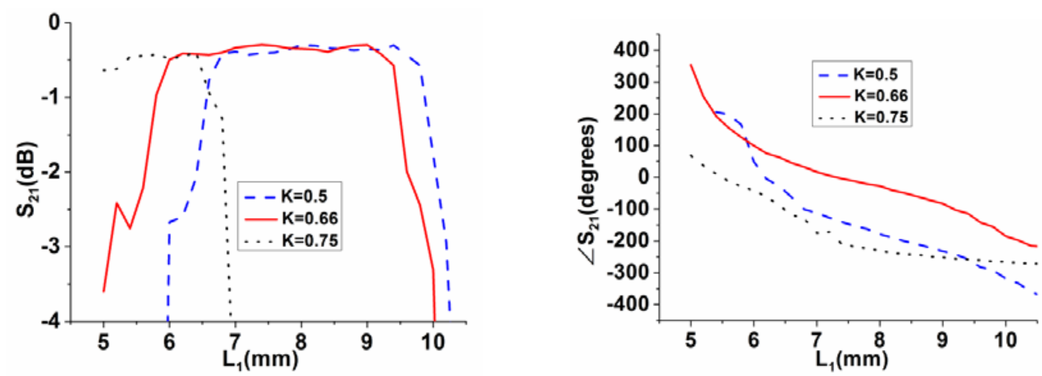


Figure 2. Transmission magnitude and phase versus the element dimension L_1 at the center frequency of 9.5 GHz ($W = 0.3$ mm, $K = 0.66$).



(a) (b)

Figure 3. Transmission coefficients for different W at the center frequency of 9.5 GHz ($K = 0.66$). (a) Magnitude and (b) phase.

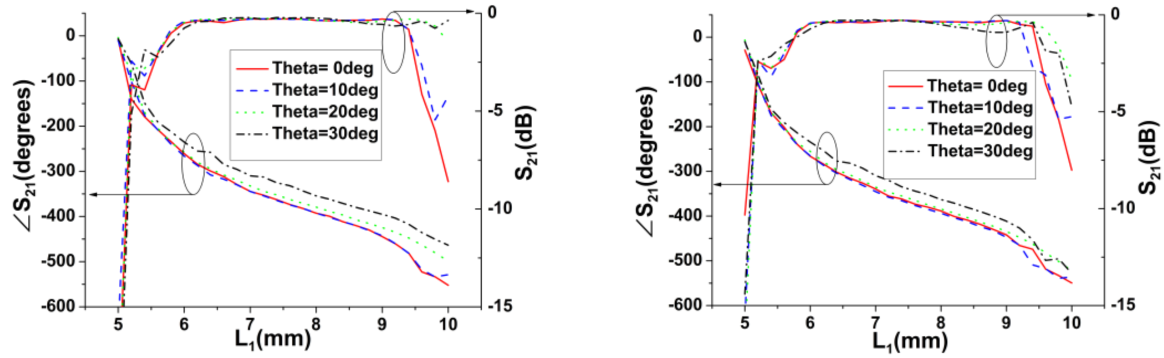


(a) (b)

Figure 4. Transmission coefficients for different K at the center frequency of 9.5 GHz ($W = 0.3$ mm). (a) Magnitude and (b) phase.

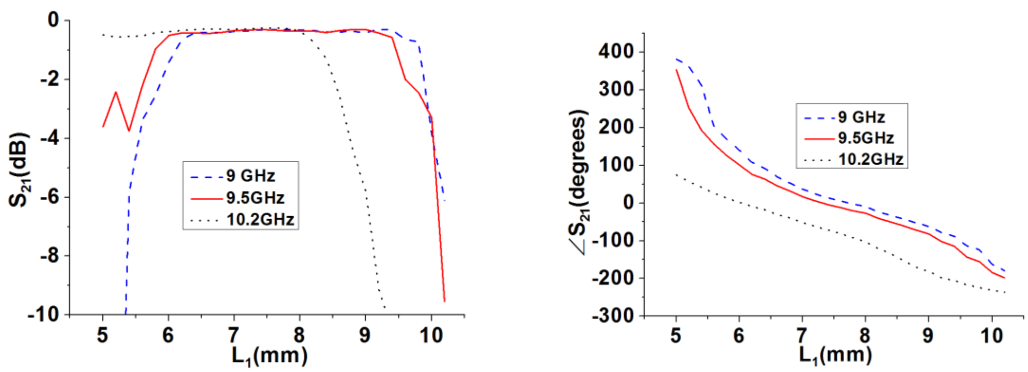
transmission magnitude and phase. When K is equal to 0.5 and 0.75, the operating ranges of the transmission magnitude and phase do not agree with each other.

In the design of the element, a normally incident wave is assumed. Actually, the majority of the transmitarray cells are illuminated by oblique incidence waves. So it is worthy to present the performances of the double-petal loop element under oblique incidence waves. Figure 5 demonstrates the variations in the transmission magnitude and phase at different oblique incidence angles. For TM



(a) (b)

Figure 5. Transmission magnitude and phase of the unit cell versus L_1 for different incident angle at the center frequency of 9.5 GHz ($W = 0.3$, $K = 0.66$). (a) TM mode, (b) TE mode.



(a) (b)

Figure 6. Transmission coefficient versus the element dimension L_1 for different frequencies ($W = 0.3$, $K = 0.66$). (a) Magnitude and (b) phase.

mode, with the increase of incidence angle θ, it can be noticed that the variations of both transmission magnitude and phase are acceptable. For TE mode, with the increase of incidence angle θ, there are small variations of the transmission magnitude and phase, except a bit descends at the element dimensions ($8\,\text{mm} < L_1 < 9\,\text{mm}$) with oblique incidence angle as high as $\theta = 30°$.

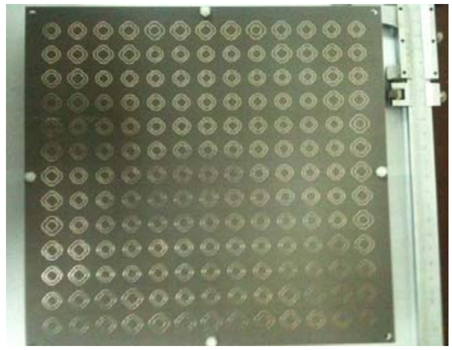
Magnitude and phase response versus length L_1 for different frequencies (9.0–10.2 GHz) are also researched, and the results are shown in Figure 6. It can be concluded that the proposed transmitarray element has a wide bandwidth.

According to the analysis of the proposed transmitarray element, it can be concluded that the element, consisting of double petal loops, can improve the bandwidth characteristics for a moderate size microstrip transmitarrays very well.

3. EXPERIMENTAL VALIDATION

In order to validate the effectiveness of the double-petal loop element, a prime-focus 676-element transmitarray is fabricated and measured. The transmitarray is fabricated on a 2 mm-thick dielectric substrate with $\varepsilon_r = 2.65$ and $\tan\delta = 0.02$. The separation between substrate layers is $H = 8$ mm. Photographs are shown in Figure 7. Both aperture size D and focal distance F of the array are 195 mm, thus the ratio of F/D is equal to 1.

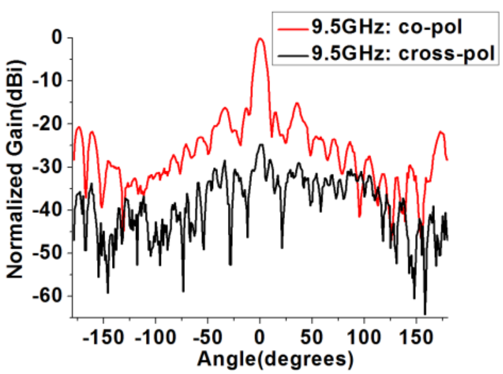
Figure 8 presents the measured radiation patterns of both co-polarization and cross-polarization in E-plane and H-plane at 9.5 GHz. It can be seen that the measured isolation between the two orthogonal polarizations is about 35 dB in the broadside direction. The peak gains against frequencies from 8.5 to



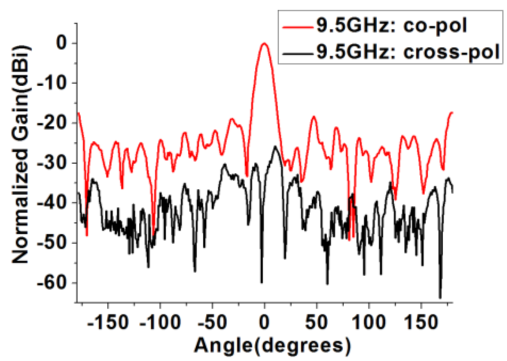
(a)

(b)

Figure 7. Photographs of the designed 676-element transmitarray: (a) top view and (b) side view.



(a)



(b)

Figure 8. The measured radiation patterns of the designed 676-element transmitarray. (a) E-plane, (b) H-plane.

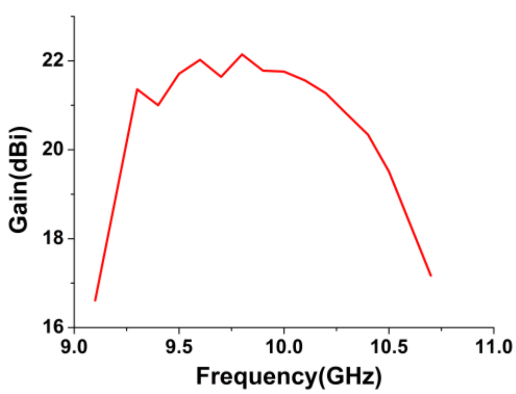


Figure 9. Measured gain of the designed 676-element transmitarray.

10.5 GHz are measured and shown in Figure 9. The aperture efficiency is found to be 31% at 9.8 GHz. The beam widths difference between E-plane and H-plane is mainly due to the influence of the feed. It can be seen that the bandwidth, found from the obtained gain variation with frequency (1 dB drop is considered here), is about 10.2% (from 9.3 to 10.3 GHz), and the peak gain is about 22.15 dBi at 9.8 GHz.

4. CONCLUSION

This paper demonstrates a design of broadband transmitarray antenna by using a novel double-petal loop element as the unit cell element. The double-petal loop element achieves a 360° transmission phase range with a transmission magnitude better than −2.4 dB. By using this type of element, a 676-element transmitarray operating at 9.5 GHz has achieved 1-dB gain bandwidth of 10.2% and good radiation pattern.

REFERENCES

1. Ryan, C. G. M., M. Reza, J. Shaker, J. R. Bray, Y. M. M. Antar, and A. Ittipiboon, "A wideband transmitarray using dual-resonant double square rings," *IEEE Transactions on Antennas Propagation*, Vol. 58, No. 5, 1486–1493, May 2010.
2. Bialkowski, M. E. and H. J. Song, "A Ku-band active transmit-array module with a horn or patch array as asignal launching/receiving device," *IEEE Transactions on Antennas Propagation*, Vol. 49, No. 4, 535–541, Oct. 2001.
3. Ellinger, F., H. Jackel, and W. Bachtold, "Varactor-loaded transmission-line phase shifter at C-band using lumped elements," *IEEE Trans. Microw. Theory Tech.*, Vol. 51, No. 4, 1135–1140, 2003.
4. Kaouach, H., L. Dussopt, J. Lantéri, R. Sauleau, and Th. Koleck, "Wideband low-loss linear and circular polarization transmit-array in V-band," *IEEE Transactions on Antennas Propagation*, Vol. 59, No. 7, 2513–2523, Jul. 2011.
5. Abdelrahman, A. H., A. Z. Elsherbeni, and F. Yang, "Transmitarray antenna design using cross slot elements with no dielectric substrate," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 177–180, Feb. 2014.
6. Abdelrahman, A. H., A. Z. Elsherbeni, and F. Yang, "High gain and broadband transmitarray antenna using triple-layer spiral dipole elements," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 1288–1291, 2014.
7. Lau, J. Y. and S. V. Hum, "A wideband reconfigurable transmitarray element," *IEEE Transactions on Antennas Propagation*, Vol. 60, 1303–1311, Mar. 2012.
8. Mahmoud, A. and A. Kishk, "Aperture coupled strip-line patch transmitarray," *IEEE Antennas Propag. Soc. Int. Symp. (USNC-URSI)*, 2015.
9. Mahmoud, A. E., W. Hong, Y. Zhang, and A. Kishk, "W-band multilayer perforated dielectric substrate lens," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 734–737, 2014.
10. Pozar, D. M., "Flat lens antenna concept using aperture coupled microstrip patches," *Electronics Letters*, Vol. 32, 2109–2111, Nov. 1996.
11. Clemente, A., L. Dussopt, R. Sauleau, P. Potier, and P. Pouliguen, "Wideband 400-element electronically reconfigurable transmitarray in X band," *IEEE Transactions on Antennas Propagation*, Vol. 61, No. 10, 5017–5027, Oct. 2013.
12. Padilla, P., A. M.-Acevedo, M. S.-Castañer, and M. S.-Pérez, "Electronically reconfigurable transmitarray at Ku band for microwave applications," *IEEE Transactions on Antennas Propagation*, Vol. 58, No. 8, 2571–2579, Aug. 2010.
13. De la Torre, P. P. and M. Sierra-Castaner, "Design and prototype of a 12-GHz transmit-array," *Microw. Opt. Technol. Lett.*, Vol. 49, No. 12, 3020–3026, Dec. 2007.
14. Kamada, S., N. Michishita, and Y. Yamada, "Metamaterial lens antenna using dielectric resonators for wide angle beam scanning," *Proc. IEEE Antennas Propag. Soc. Int. Symp. (APS-URSI)*, 1–4, 2010.
15. Cheng, Q., H. F. Ma, and T. J. Cui, "Broadband planar Luneburg lensbased on complementary metamaterials," *Appl. Phys. Lett.*, Vol. 95, No. 18, 181901-1–181901-3, Nov. 2009.