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High Gain and Wideband Stacked Patch Antenna for S-Band Applications

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Abstract—In this paper design of a stacked circular patch antenna is presented for high gain and wideband applications. The main radiator of this design is a circular patch antenna, which is fed by using a coupling mechanism. Wide impedance bandwidth of 40% and linear polarization of gain 9.5 dBi at the center frequency of 2.4 GHz is measured. The antenna gain is further increased by using regular period of N circular patch directors on top of the main radiator. The first director is placed in a distance of about one half of the wavelength and the next directors are placed with regular distances of about a quarter of the wavelength. The antenna gain is tuned and increased with the number of the directors in the range of 9.5–16.5 dBi with N up to seventeen. The antenna impedance change due to the added directors is adjusted by using two parasitic circular patches between the main radiator and the first director. A prototype antenna is designed, manufactured and measured. The antenna operation can be further extended using dual feed geometry in which we can obtain two orthogonal radiation patterns or circular polarizations.

1. INTRODUCTION

Use of high gain antennas in microwave frequencies is essential for wireless communications and RADAR. High gain can be achieved by using a reflector antenna or an array antenna configuration. For the applications in L- and S-bands the efficiency of a small size reflector antenna is constrained by the large feed blockage and the feed impedance which is significantly influenced with the reflector surface due to the small distance of the feed to the metal surface of the reflector. This reduces the antenna gain and impedance bandwidth of a reflector antenna. Using array antenna configuration can provide higher efficiency and larger bandwidth. The essential part of any array antenna is its single element radiator. Using a high gain element can reduce the array antenna surface significantly. For instance, increasing the element gain by 6 dB can reduce the surface of a planar array by 75%. Therefore, the design of a high gain and wideband single element antenna is considered in this paper for usage in S-band. Moreover, the proposed single antenna element design can be easily configured to maintain various antenna gain and radiation pattern for an array antenna usage.

Periodic structures such as partially reflective surface (PRS) are used to increase the gain of single element antenna. Fabry-Perot cavity type antennas is an example of using PRS which significantly increases the gain and directivity of the primary source such as a dipole [1–3]. The large profile of these antennas can be reduced by using planar artificial magnetic conductor (AMC) ground planes [4–6]. The other approach to increase the gain of a patch antenna is by using high impedance surfaces (HIS) around the radiating element by eliminating the surface waves [7], however the gain increment using this technique is marginal indeed they can control the side lobe and back lobe of the antenna. The aforementioned methods for increasing the antenna gain requires realization of a periodic surface,

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where at least five periods of resonating unit cells are used. Thus, the antenna surface is increased in the order of 2–3λ compared to the required resonance length of $\lambda/2$. In addition, the impedance and gain bandwidth of these antennas is limited in the order of 10–15%, despite the significant efforts had been devoted to increase these performance factors. Moreover, the increased surface in these antennas limits the element antenna usage in array configuration due to the inherent large distances among the elements that is much more than $\lambda/2$.

The single element antenna gain and bandwidth can be increased by using the coupled feed mechanisms [7, 8] or through the patch shaping in a three-dimensional form [9]. The reported maximum gain by these techniques is around 9.5 dBi and the impedance bandwidth of 20%.

In this paper, we use the depth profile of an antenna instead of its surface to increase the single element gain. The concept for increasing the antenna gain is similar to using log-periodic or Yagi antenna implementations, but using a circular patch as the main radiator and parasitic elements for the impedance tuning. By using the circular stacked patch geometry, we can apply two 90 degrees physically oriented feeds to generate two orthogonal radiation patterns with high isolation between the feeds. Also, circular polarizations are easily to implement. The paper is organized as follows. In Section 2, design of a single element circular patch antenna by using coupled feed mechanism as the main radiator is presented. In Section 3, the approach for antenna gain increment by using periodic directors is described and the simulation and measurement results are provided. In Section 4, the antenna simulation for generating two orthogonal polarizations or a circular polarization is presented. Section 5 concludes this paper.

2. PATCH ANTENNA DESIGN

The main radiator of the design is a circular patch antenna on top of a ground plane. The patch antenna is fed through a coupling mechanism by using a circular disc plate. This feed mechanism can provide large bandwidth and high gain operation compared to the direct feeding of the circular patch [7, 8]. The antenna is designed and optimized to provide impedance coverage for S-band with maximum gain. The optimized antenna structure and the dimension details are shown in Fig. 1. The coupling disc is fed by using a coaxial line in which the inner conductor excites the disc and the outer conductor is joined to the circular ground plane. TM11 mode of the circular patch antenna is excited using this feeding mechanism. Thus, a linearly polarized radiation pattern is generated. The antenna simulation is conducted using CST Microwave Studio. The antenna is manufactured and measured. Fig. 2 shows the simulated and the measured return loss of the antenna. As shown, the antenna is matched to the 50 ohms impedance of the feed for the frequency range of 2000–2800 MHz, with return loss better than 10 dB. The small discrepancy is due to the manufacturing errors. Fig. 3 shows the simulated E-plane

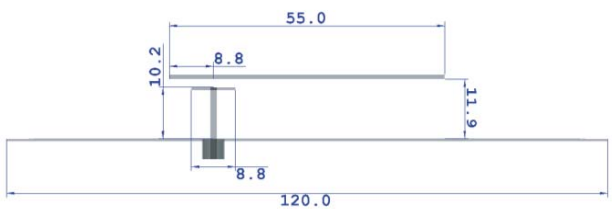


Figure 1. Side view of the circular patch antenna; The patch antenna is fed via a coupled feed disc on top of a circular ground plane.

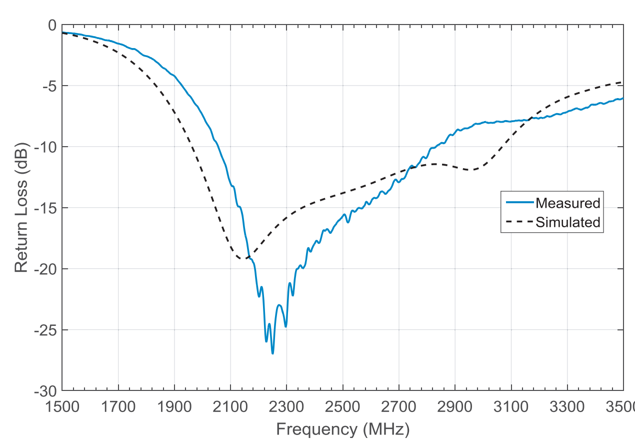
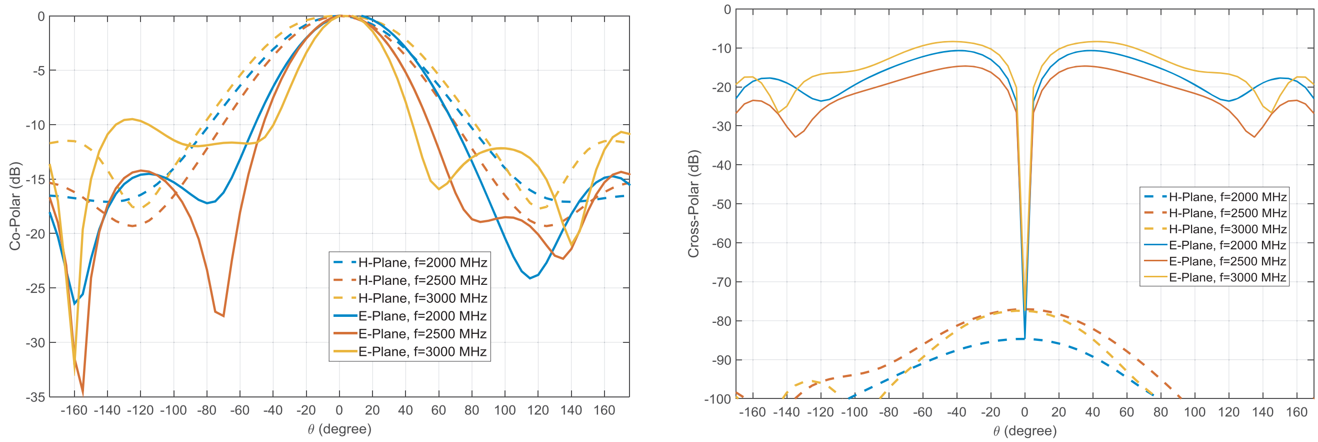


Figure 2. Measured and simulated S-parameter of the patch antenna.



(a) (b)

Figure 3. Simulated radiation pattern for E-plane and H-plane at 2000, 2500 and 3000 MHz. (a) Co-polar pattern, (b) cross-polar pattern.

and H-plane radiation patterns of the antenna for co-polar and cross-polar. The antenna radiation pattern is linearly polarized and has directional beam for the frequency range of 2000–3000 MHz. The gain varies with frequency within 8 to 10 dBi (see Fig. 5 for the gain plot of the patch antenna). The antenna pattern deteriorates above 3100 MHz due to the excited higher order modes of the circular patch. This makes difficult to use the antenna above this frequency even if a matching circuit is applied. The antenna radiation pattern is not symmetric for E- and H-planes and has narrower beamwidth for the E-plane.

3. PATCH ANTENNA WITH PERIODIC DIRECTORS

The antenna gain is increased by adding several directors above the circular patch. Fig. 4 shows the proposed new design. By using only one circular patch of diameter 40 mm (0.3λ) above the main radiator in a distance of 53.6 mm (0.45λ, where λ is the wavelength at 2500 MHz) the maximum gain

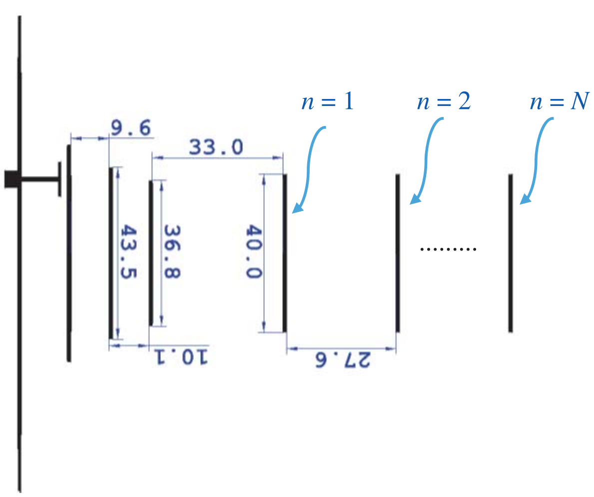


Figure 4. Patch antenna with N directors and two parasitic patches for impedance and gain adjustments. The distance among the directors are constant.

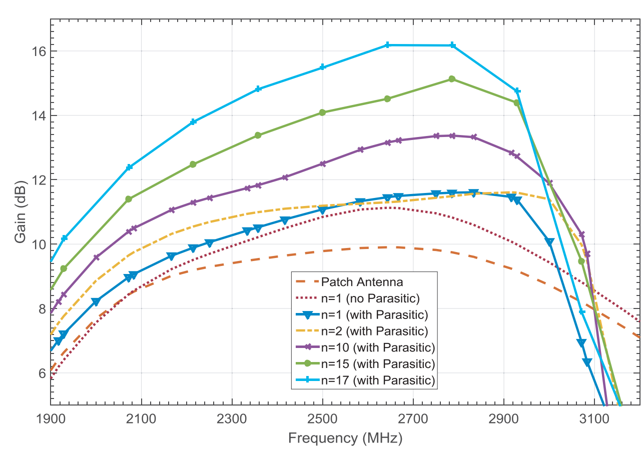


Figure 5. Simulated antenna gain versus frequency for n directors, the effect of the parasitic elements on the antenna gain is also illustrated.

increment of 1.2 dB is achieved compared to the original patch antenna. The return loss of the antenna becomes worse due to the wave reflections from the first director, in which the return loss is increased to 7 dB at the center frequency. To retain the available wideband matching, two circular parasitic elements with optimized size and distance are added between the main radiator and the first director patch. The detailed position and dimension of the parasitic elements are illustrated in Fig. 4. The optimization goal was to maximize the gain and provide the impedance matching. Using these parasitic elements, the antenna matching with return loss less than 10 dB can be retained, and the antenna gain is further increased. Fig. 5 shows the antenna gain versus frequency for different antenna configurations with and without the parasitic elements. The antenna gain for the case of the original circular patch is also illustrated for comparison. As shown, the antenna gain with one director and two parasitic elements is more than the case without the parasitic elements, for whole frequency band. The maximum gain of 11.8 dB is obtained. The problem with adding the directors is that the antenna pattern deteriorates above 3000 MHz that causes a rapid gain loss.

By adding periodic pattern of directors with a distance of 27.6 mm ($\lambda/4$) above the first director, the antenna gain is increased gradually (see Fig. 5 for different n values). In this case the antenna matching is slightly altered, but remains below 10 dB for the whole frequency range and n directors. For the case of $n = 2$ the antenna gain increases at the lower band and it has small effects for the upper band. By using ten, fifteen and seventeen directors, the maximum antenna gain is increased to 13.4, 15.2 and 16.2 dBi, respectively. To achieve a gain of 17.5 dBi, the number of directors must be increased to 34. The gain reduction above 3000 MHz is considerable with adding the directors.

To manufacture the antenna, it is required to hold the director patches mechanically on top of the main radiator. For this purpose, we can consider a dielectric holder at the sides of the patches or a rod type holder passing through the center of the patches. The holder should not alter the distribution of the electric field in the space between the metals and the current on the metal surfaces. For this clarification, numerical calculations of the electric field and the current distribution on the metal parts are conducted. Fig. 6 shows the contour graph of the electric field. As shown, the field intensity tends to zero at the center of the metal circles and the field intensity is considerable on the rim of the circular patches in which the current is dense. Therefore, we have used a rod type holder instead of the holder at the sides of the structure expecting little influence on the antenna characteristics.

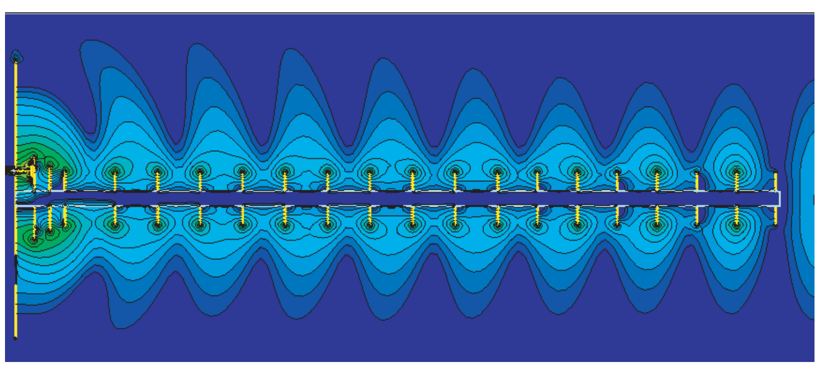


Figure 6. Contour plot of the electric field intensity at 2500 MHz. The high field intensity at the circular patch rims are visible and the field along the center of the circular patches is very small that is negligible which leads to an effective use of a dielectric rod as a mechanical holder.

A prototype antenna is manufactured by using $n = 17$ director elements (see Fig. 7). To hold the director discs on top of the main radiator antenna, a dielectric rod is used that passes through the generated holes at the center of the metal circles and is fixed to the ground plane. The dielectric rod material is hard solid composite with approximate dielectric permittivity of 3. The diameter of the rod is 10 mm. The circular patches have been fixed to the rod using glue at the predetermined locations. The effect of dielectric rod on the antenna gain and impedance performance are investigated that is negligible. The diameter of holes can be increased up to 20 mm without considerable changes on the

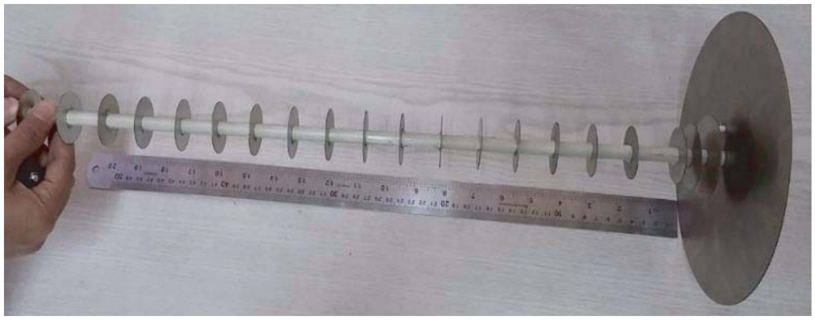


Figure 7. Manufactured prototype antenna with $n = 17$ directors; Total length of the antenna is 510 mm.

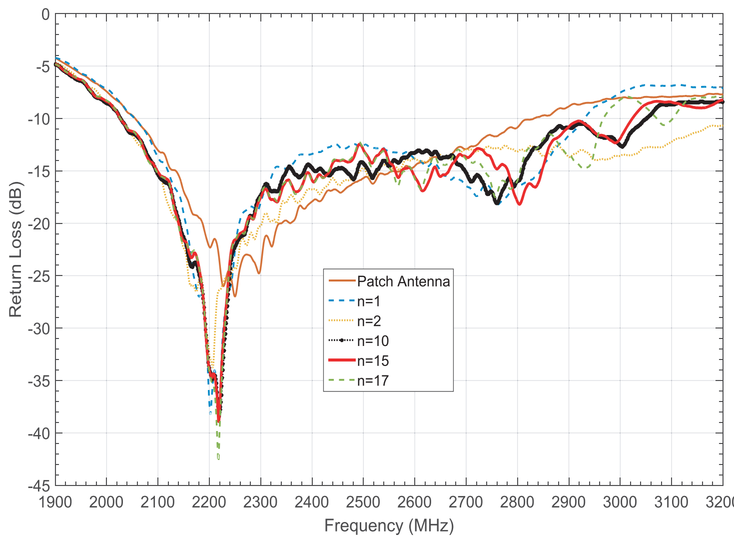


Figure 8. Measured return loss versus frequency for the patch antenna and the antenna with n directors including the parasitic elements.

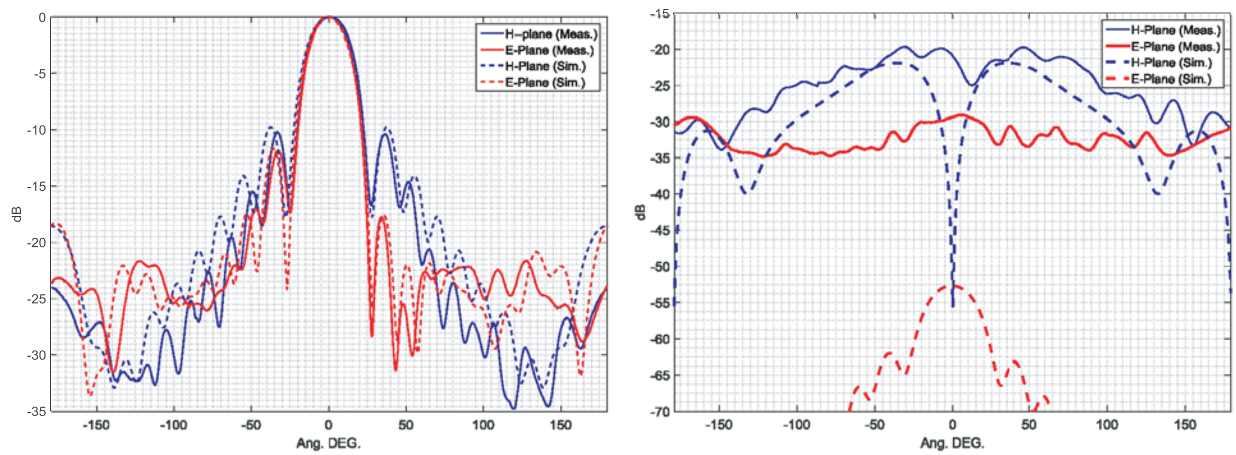
antenna gain and bandwidth performance, however the antenna matching becomes worse which needs adjustment.

The manufactured antenna is measured for the return loss using a calibrated network analyzer, in which the return loss is measured by adding each of the director elements. Fig. 8 shows the measured return loss for different number of directors. The oscillations at the return loss plot with increasing the number of n directors show the back and forward wave reflections at the periodic structure that causes the coherent phase addition of the wave and thus the antenna gain enhancement.

The radiation pattern of the antenna is measured in an anechoic chamber with farfield facility. Fig. 9 shows the measured co-polar and cross-polar radiation pattern for E- and H-plane for the prototype antenna with $n = 17$ directors. The simulated radiation pattern is also illustrated for comparison. Very close agreement among the results of simulation and measurement are achieved. As shown in Fig. 9(a), the 3 dB pattern beamwidth for H- and E-planes are 28.8 and 26.4 degrees, respectively. The antenna radiation pattern is more symmetric compared to the radiation pattern of the single patch antenna. The reason is that E- and H-field phase plans by progressing along the periodic structure becomes planar (see Fig. 6), therefore an axially symmetric pattern in the farfield is generated.

The antenna cross polarization is less than 20 dB for the measured results.

Figure 10 shows the simulated and the measured antenna gain. The maximum gain of 16.3 dBi is achieved. The measured gain at the lower frequency band is about 0.7 dB below the simulations due to the calibration of our reference antenna in the anechoic chamber.



(a) (b)

Figure 9. Measured and simulated co-polar and cross-polar radiation pattern of the antenna with $n = 17$ directors at 2500 MHz.

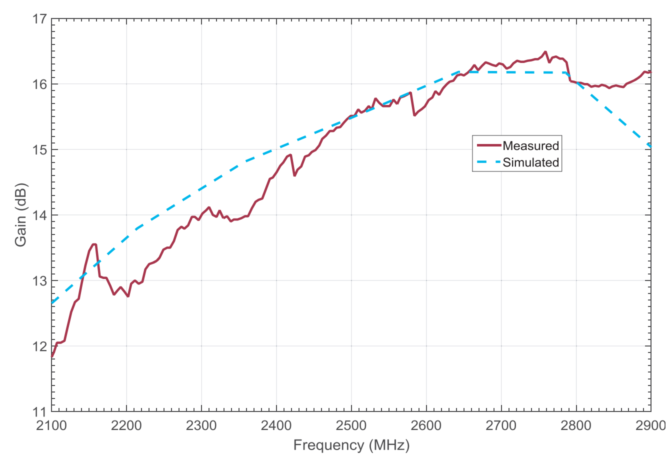


Figure 10. Measured and simulated antenna gain with $n = 17$ directors.

4. STACKED PATCH ANTENNA WITH POLARIZATION DIVERSITY

The stacked patch antenna geometry is used in a configuration to provide two orthogonal polarization or circular polarization. For this purpose, the aforementioned antenna geometry is fed via two 90 degrees physically rotated coupling discs. The same geometry and size of the circular patches and the feed disc are used. Two coaxial feed lines are applied to excite the coupling discs. The antenna is simulated using CST MWS. The simulated mutual coupling between the antenna ports is shown in Fig. 11. The coupling in the frequency range of 2200–2800 MHz is below -18 dB that permits to realize two independent orthogonal radiation patterns by feeding each of the antenna ports. By applying a 90 degree phase shift between the two feed lines, i.e., using a two way 90 degree power splitter such as QCS-332+ from Minicircuits we can excite the antenna Using this feeding approach RH or LH circular polarizations depending on the phase lag between the antenna ports can be obtained. Due to the radiation pattern symmetry for E- and H- planes, the cross polarization ratio of the circular polarized antenna is below 3 dB for 2150–2800 MHz (see Fig. 12). Therefore, one feature of the stacked patch antenna geometry is the possibility to generate two orthogonal polarizations or RH/LH circular polarization.

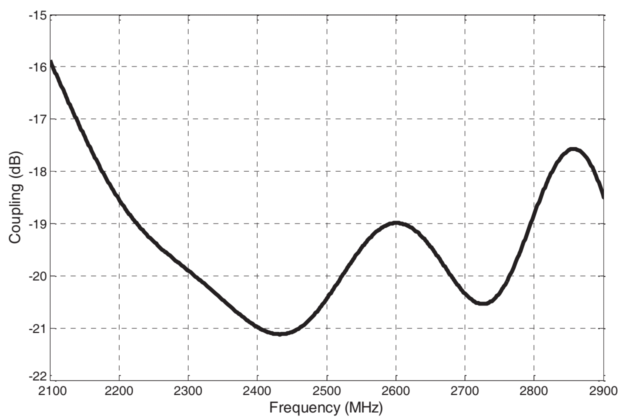


Figure 11. Simulated coupling (dB) between the two 90 degree physically rotated feeds versus frequency in the dual feed antenna geometry.

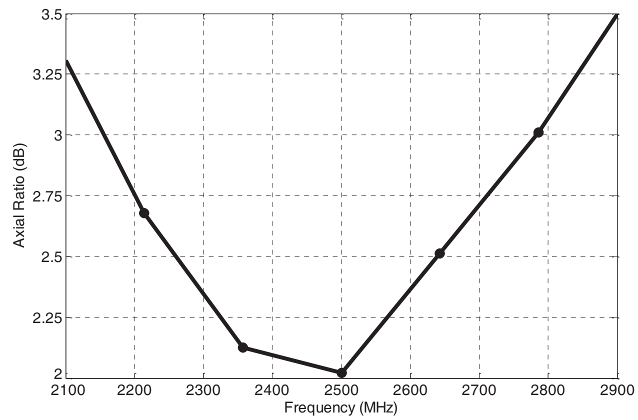


Figure 12. Simulated axil ratio (dB) versus frequency of the dual feed antenna geometry with 90 degree phase shifter.

5. CONCLUSIONS

A wideband circular patch antenna is designed using coupled feed mechanism that covers S-band with 44% of impedance and gain bandwidth, with maximum gain of 10 dBi. The antenna is linearly polarized, and the radiation pattern is not symmetric in the E and H-planes. The antenna gain is increased by extending the depth profile of the antenna by adding periodic director patches above the main radiator. The first director is placed at about $\lambda/2$ above the main radiator, and the rest of the directors are placed with a period of $\lambda/4$. The antenna wideband matching is influenced with directors, in which two parasitic patches are added between the main radiator and the first director to attain the wideband impedance matching. Adjustable antenna gain in the range of 10–16.4 dB can be obtained by using one to seventeen director elements. The antenna gain increment is marginal by using higher number of directors. The radiation pattern of the antenna becomes symmetric with increasing the directors, and pencil beam pattern is achieved with linear polarization. Using a dual-feed configuration, two independent orthogonal polarizations can be achieved due to the high isolation between the feeds. LH and RH circular polarizations are achieved by using a two-way 90-degree power splitter between the feeds.

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