

Low Reflection Coefficient Ku-Band Antenna Array for FMCW Radar Application

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Abstract—A radar for decisive target detection and tracking requires wideband, high return loss, and high efficiency antenna array. In this paper, a 16 element stacked-patch microstrip antenna array is presented at Ku-band with very low reflection coefficient for radar system. An aperture coupled feeding approach for a stack patch antenna is employed for wide bandwidth. A thin and low-loss tangent material, Taconic TLY-5, is used in the design of an antenna array to minimize the surface current loss and dielectric loss. Moreover, the antenna is designed with good impedance match, -30 dB, for high efficiency, by optimizing the stacked patches and utilizing reactive loading from u-slit on patch. For a low reflection coefficient antenna array over a wide bandwidth, an adequate feeding network consists of a compact and meandering stripline with metal-post around it is developed. The stripline configuration with metal-post minimizes crosstalk and lateral leakage. The feeding network developed has low reflection coefficient of -30 dB for the target band. The simulated feeding network loss is also low, 0.5 dB. The overall size of the 16 element array is compact, $295 \text{ mm} \times 30 \text{ mm}$ ($14\lambda \times 1.425\lambda$). The antenna array performance gives a reflection coefficient of -30 dB in the range of $14\text{--}14.5$ GHz and total efficiency of 80% . The gain of the array is 21.5 dBi at 14.25 GHz.

1. INTRODUCTION

The detection, tracking, and localization techniques of several radar based drones are emerging with advances in smaller military and commercial drones [1]. A Ku-band short-range pulse battlefield drone detection radar is experimented in [2] for small RCS drones with high probability detection for distance up to 2 Km. A Frequency Modulated Continuous Wave (FMCW) radar system has also been investigated for small drone detection [3, 4] with higher range discrimination capability due to wide bandwidth [5]. An FMCW radar for small drone detection with higher range discrimination demands an efficient, low loss and broadband antenna. Antenna efficiency is improved by reducing dielectric loss and impedance mismatch. It is very common to observe a well-matched antenna with very low reflection coefficient of the order of -20 to -30 dB and even less for a narrow band or for a single operating frequency in the literature [6–8]. However, for broadband antennas -10 dB reflection coefficient is acceptable, and rarely a wideband single element has been reported to have a low reflection coefficient of -20 dB to -30 dB or less. Moreover, in wideband linear arrays and planar arrays, it is difficult to maintain very low reflection coefficient over the entire bandwidth even though their single element designed has low reflection coefficient [9–11]. The main impediment in achieving very low loss reflection coefficient in array setup is mutual coupling and loss of signal integrity in a complex feeding network of array. An antenna array design with reflection coefficient well below -30 dB over operating band is not considered, in particular, for FMCW radar or any radar system. Nevertheless, a very low reflection coefficient microstrip antenna array is suitable for any radar system because it can reduce high power loss in reflection from antenna in a high power transmitter radar system. Also, FMCW radars suffer from Tx

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phase noise leakage to the Rx which deteriorates its detection performance, but as per antenna part this leakage can be subdued with low reflection coefficient antennas [4, 12, 13].

In this paper, we propose a compact, low loss, and very low reflection coefficient (-30 dB) stacked microstrip antenna array for a Ku-band (14–14.5 GHz) FMCW radar. Stacked patch antenna elements are a wideband antenna, which we enhance further with application of aperture coupling feeding approach. We improve the impedance matching of the designed antenna element with the reactive tuning using a u-slit etched over it. The low reflection coefficient of an antenna element and its bandwidth is required to be complemented with a suitable well matched and wideband feeding network for our antenna development. A meandering corporate stripline feeding network is developed with good impedance matching below -30 dB over 14–14.5 GHz. Stripline feeding is used to reduce loss due to radiation which is a general issue with microstrip lines feeding. The stripline feeding network used here is shielded by metal posts to achieve broad bandwidth, minimize crosstalk, and reduce lateral leakage of stripline. Moreover, low permittivity, low-loss, and thin material utilization minimize surface current loss and dielectric loss. The element design of the array is discussed in Section 2. A compact wideband stripline feeding network is presented in Section 3. The full array performance and design are presented in Section 4. The fabricated model and measured results are presented in Section 5 and conclusion in Section 6.

2. SINGLE ELEMENT DESIGN

Numerous techniques have been proposed in literature to improve microstrip antenna bandwidth, and these techniques are well presented in [14, 15]. There are three parts in a microstrip antenna design — microstrip patch dimension, substrate material selection, and feeding approach, where a patch dimension is significant for its resonating frequency, and the choice of substrate material is critical for antenna bandwidth and efficiency. The bandwidth of a single patch antenna increases with thickness and with lower permittivity of a substrate. However, a thick substrate causes surface current loss and increases mutual coupling in an array, but surface current can be in check with low permittivity. Among feeding approaches, aperture coupled feeding provides wide bandwidth with several advantages over direct feeding, e.g., no undesired radiation and easier to improvise impedance matching. Along with that, a multilayer patch configuration where multiple patches can be optimized to resonate close to each other yields wider bandwidth than regular single patch configuration. Moreover, slots over the patches can also be utilized to enhance the antenna bandwidth [16].

A stack patch antenna with aperture coupled feeding using stripline has been used considering the above-mentioned factors for the design of an array element to obtain the desired performance. An exploded view of the multilayer Ku-band microstrip antenna element designed for broadband and high proficiency performance is shown in Figure 1(a). A stripline feed of $50\ \Omega$ and an H -shaped slot (slot width = 0.63 mm, $H_1 = 4.9$ mm and $H_2 = 1.85$ mm) on the top ground plane (layer 1 and layer 2) is used to achieve an aperture coupled feeding. The H -shaped coupling slot provides high coupling and improves impedance matching [17, 18]. There are two patches — stack patch (on layer 4) and resonator patch (on layer 3) with a separation of ‘ h ’ mm between them. Further, the conventional stack patch model is modified with a resonating u-slit carved on the resonator patch to broaden the impedance matching bandwidth. Taconic TLY-5 ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$), a low-loss laminate, of 0.5 mm thickness is utilized for making the resonator patch and stripline feeding in order to minimize the dielectric loss and surface current [19]. A rohacell foam is used to support the stack patch in simulation and fabrication.

A simple analysis of the stack patch antenna is difficult to obtain, and often full wave analysis is performed. A general guideline for stack patch design is that the two-patch length determines the upper and lower limits of the operating frequency. An additional resonance is achieved with a slit over the resonator patch, consequently improving the antenna bandwidth. The coupling slot can also be tuned to resonate to further widen the bandwidth. The additional elements provide more design parameter to control and optimize the antenna model. These parameters are utilized in our design for improving the reflection coefficient of the antenna over 14–14.5 GHz band. The stack patch, resonator patch, and u-slit can be represented by RLC component with a corresponding admittance as shown by equivalent circuit model of the stack patch in Figure 1(b). An equivalent circuit model of stacked patch [15, 20] can

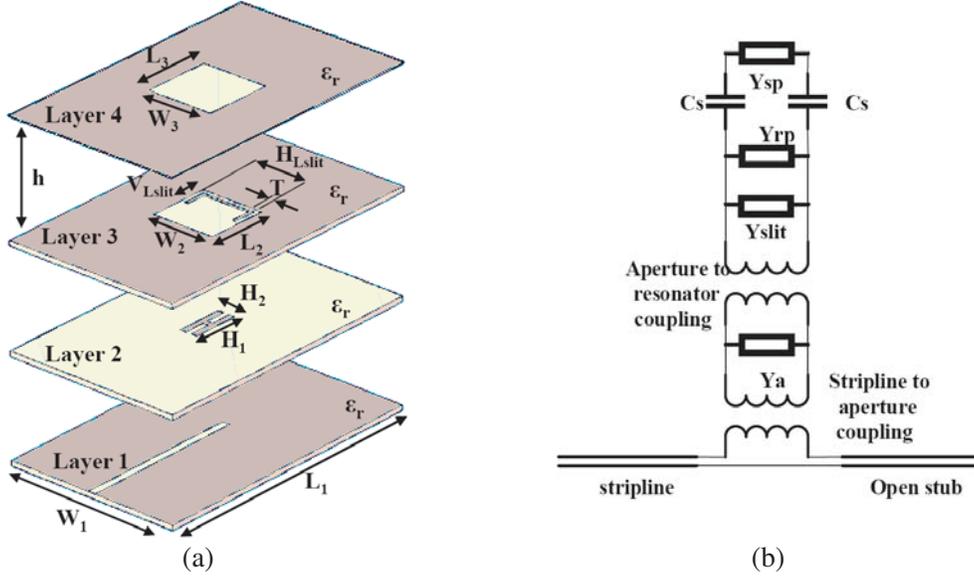


Figure 1. Single Stack Patch Antenna (a) model (The dimension (in mm): $L_1 = 30$; $L_2 = 6.40$; $L_3 = 7.12$; $W_1 = 18.385$; $W_2 = 6.65$; $W_3 = 6.97$; $h = 1.7$), and (b) equivalent circuit (Y_{sp} : stacked patch admittance, Y_{rp} : resonator patch admittance, Y_{slit} : u-slit admittance, Y_a : aperture admittance, C_s : staked layer capacitance, C_{slit} : u-slit capacitance).

provide insight for its design and performance tuning. The u-slit admittance (Y_{slit}), resonator patch admittance (Y_{rp}), and stack patch admittance (Y_{sp}) are in-parallel in the equivalent circuit model which makes the equivalent input impedance:

$$Y_{eq} = Y_{slit} + Y_{rp} + Y_{sp} \quad (1)$$

Y_{slit} , Y_{rp} , and Y_{sp} are related to the physical dimension of u-slit, resonator patch, and stack patch, respectively, and can be obtained from the formulas given in [15, 20, 21]. A stack patch antenna with a u-slit on resonator patch, as mentioned earlier, is a wideband antenna, whose impedance matching can be tuned with a variation of dimension of u-slit, resonator patch, and stack patch. In our design, impedance matching of the wideband stack patch antenna is improved by optimizing inductive and capacitive loading (Y_{slit}) due to the u-slit. The u-slit consists of 3 parts; 2 vertical slits of length V_{Lslit} and one horizontal slit of length H_{Lslit} . The slit width is T in all 3 parts. Initially a stack patch model is designed for the targeted frequency of 14–14.5 GHz. Then the u-slit is etched on the resonator patch, and its dimension is tuned to improve the impedance matching. The antenna simulated result of reflection coefficient in Figure 2(a) and the corresponding Smith chart plot in Figure 2(b) shows that with u-slit parameter variation (i.e., changing Y_{slit}) impedance matching for the desired frequency band, 14–14.5 GHz, can be altered and improved to -30 dB. With the u-slit parameter change we can observe that % bandwidth does not change much; however, there is significant improvement in reflection coefficient. From the Smith chart plot, Figure 2(b), a tight knot at center for different u-slit parameters can be observed; however, the knot moves away from center in capacitive or inductance zone of Smith chart due to reactive effect of u-slit parameter variation. The optimized u-slit parameter obtained is $V_{Lslit} = 2.42$ mm, $H_{Lslit} = 5.75$ mm, and $T = 0.35$ mm. The impedance matching bandwidth of -10 dB is $> 15\%$ for the designed antenna with optimized u-slit.

An impedance matching quality directly influences antenna efficiency. Total antenna efficiency is usually affected by dielectric loss, conductor loss, and return loss. A total antenna efficiency can be obtained from the product of impedance mismatch and radiation efficiency [22].

$$E_T = M_L \cdot e_R \quad (2)$$

E_T is the total efficiency, M_L the impedance mismatch ($1 - |\Gamma|^2$), and e_R the radiation efficiency. Low reflection coefficient can certainly improve antenna efficiency as per Eq. (2), and a good impedance

matched antenna is desirable in FMCW radar application for small target (e.g., drone) detection where the transmitted power is required to transmit efficiently and illuminate the target for a strong echo signal. Low reflection coefficient is also essential for minimizing leakage problem, causing saturation of receiver and consequently diminishing detection capability of FMCW radar [12]. The designed antenna has low reflection coefficient of less than -30 dB for 14–14.5 GHz, which is our target frequency range for Ku-band drone detection radar. The total and radiated antenna efficiency obtained from simulation is 99.3% and 99.4%, respectively at the center frequency, 14.25 GHz. The gain of the designed antenna owing to a high impedance match and high efficiency obtained to be 9.6 dBi at 14.25 GHz. Figure 3 shows the simulated gain of the single multi-layer microstrip antenna. The designed antenna is an efficient, well-matched, high gain, and wideband antenna for Ku-band. In order to transform the antenna element into an efficient and low reflection coefficient array, a compact feeding network with good matching over 14–14.5 GHz band is required to develop. The feeding network development is discussed in next section.

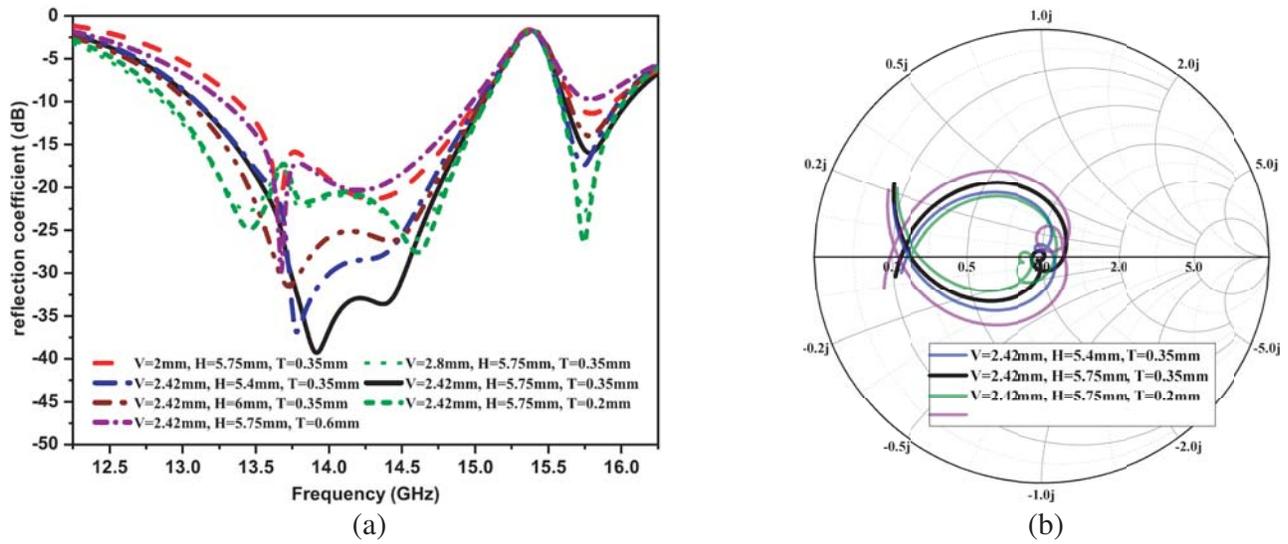


Figure 2. Single stack patch antenna characteristics (a) Return Loss Plot, and (b) Smith chart plot for various U-slit parameter (V is vertical length of slit, H is horizontal length h of slit and T is slit width).

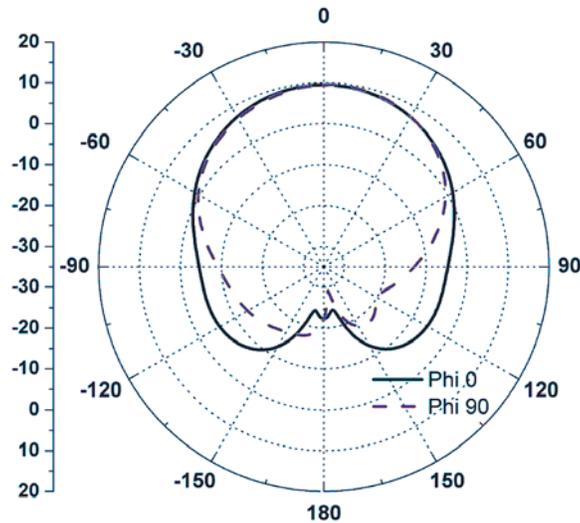


Figure 3. Single stack patch radiation pattern.

3. FEEDING NETWORK CONFIGURATION

An important aspect in the design of array is feeding network configuration. Corporate and series feeding networks are two commonly used feeding networks, where corporate feeding provides wide bandwidth, and series feeding provides a narrow bandwidth feed, but series feeding is more compact in design, and corporate feed layout takes more space. Therefore, a compact feeding network routing for corporate layout is required. Moreover, as the number of elements increases, the complexity and size of the conventional corporate feeding layout also increase. Such a complex feeding network, if implemented on the top layer of the antenna, would have generated undesired radiation which could have severely affected the antenna performance and its reflection coefficient. In our design, we choose to have a stripline feeding to minimize such undesired radiation. Also, in order to get a highly dense and compact corporate feeding layout, metal posts around the stripline are used not only to reduce crosstalk and lateral leakage but also to achieve good matching over wider bandwidth [23, 24].

Metal posts separation and distance from stripline can be controlled to increase the unimodal operation bandwidth and thus achieve a low reflection coefficient over a wide bandwidth with dense and compact layout. With the use of metal post and meandering stripline configuration, a compact corporate network is devised as shown in Figure 4(b). Compared to a conventional corporate feeding network (Figure 4(a)), the overall space acquired by the feeding network would get distributed evenly over the two sides of an antenna array. Figure 4 shows conventional and the proposed 1 : 8 power divider network over the same limited width L_1 with E -field distribution. The conventional corporate network requires to be squeezed down to fit in the limited space which could lead to crosstalk and matching performance deterioration, whereas the proposed meander stripline feeding network fits comfortably in the limited space, and with metallic post the crosstalk and performance deterioration issues are minimized. E -field distribution over the feeding network highlights the impact of metal post and meandering stripline network over conventional corporate feeding network in reducing crosstalk and maintaining signal integrity. A comparative analysis of the conventional and proposed feeding networks

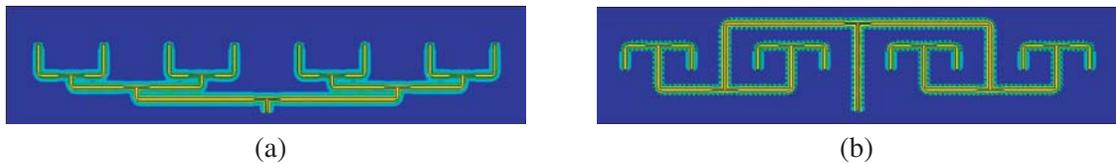


Figure 4. Conventional and proposed feeding network (a) Conventional feeding network with E -Field distribution, and (b) Proposed meandering feeding network (metallic post radius = 0.2 mm; metallic post separation = 1.3 mm).

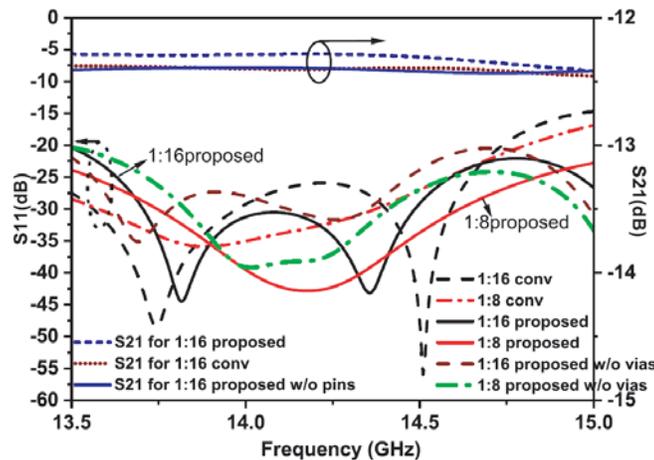


Figure 5. Comparison of conventional and proposed feeding network (with and without via).

with and without metal posts for 1 : 8 and 1 : 16 power dividers is shown in Figure 5. It can be observed that both conventional and proposed feeding networks have wideband characteristics; however, matching performance deteriorates at the target frequency range with feeding network size. The challenge to have a low reflection coefficient for 1 : 16 power divider at 14–14.5 GHz band is achieved from the meandered stripline feeding network design with metal post of radius 0.2 mm and separation of 1.3 mm. The feedline loss, as apparent from the S_{21} plot in Figure 5, is ~ 0.5 dB. The proposed layout scheme would be exceptionally advantageous with a compact size model and a larger number of elements in an array.

4. ANTENNA ARRAY DESIGN

A linear array of 16 elements is designed in this paper for a gain of 20 dBi. The 3D model of the 16 element array is shown in Figure 6. The array model consists of an array of designed stack patch antenna and 1 : 16 meandering stripline feeding network. A stripline to microstrip line transition indicated in Figure 6 is added to the meandering stripline feeding network for convenient SMA connector connection. As the feeding network is a stripline, proper connection between SMA connector and feeding network is difficult to ascertain. Therefore, stripline to microstrip line transition is included in feeding network design to establish proper connection between SMA connector and feeding network. The resonator layer (Layer 3 in Figure 1) and stacked patch layer (Layer 4 in Figure 1) dielectrics are partially removed to reduce the surface current impact by obstructing the surface current path, and thus further minimizing mutual coupling. For low mutual coupling effect, as mentioned in Section 1, low permittivity and thin dielectric substrate have been employed for the design.

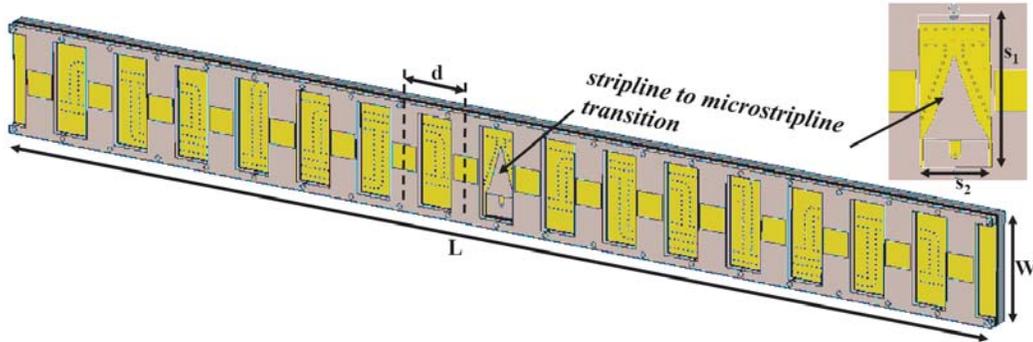


Figure 6. 16 element array design model (The dimension (in mm): $L = 294$, $W = 30$, $d =$ element separation, $s_1 = 25$, $s_2 = 10$).

In general, the key parameter in array design is the separation between the elements, ‘ d ’, satisfying the required gain and mutual coupling. A compromise is required to achieve the best of all characteristics with element spacing. Smaller separation ($< \lambda/2$) causes high mutual coupling and degrades the impedance matching as well as bandwidth, whereas larger separation ($> \lambda$) causes grating lobes in the visible region. A parametric study of array characteristics such as gain, sidelobe level (SLL), and reflection coefficient at 14.25 GHz for the designed array with different element spacings, ‘ d ’, is shown in Figure 7.

From the simulation results in Figure 7, it can be observed that the impedance matching performance of the array degrades with smaller element separation. The impedance matching is affected due to mutual coupling; however, the matching is below -10 dB for $> 0.5\lambda$ which is considered suitable for many applications. In Figure 7 it can also be observed that the gain of the antenna array improves with larger element separation, whereas there is a relatively small change in SLL. The finalized model has element separation of 0.87λ . The impedance matching with 0.87λ element separation is < -30 dB, and gain is > 20 dBi. The total efficiency of simulated antenna array for the optimized separation is found to be 80%. First, an antenna model is designed with the required reflection coefficient over 14–14.5 GHz, then a feeding network with as low as -30 dB reflection coefficient for targeted band is achieved with the proposed metal post enclosed meandered stripline, and at last, appropriate element

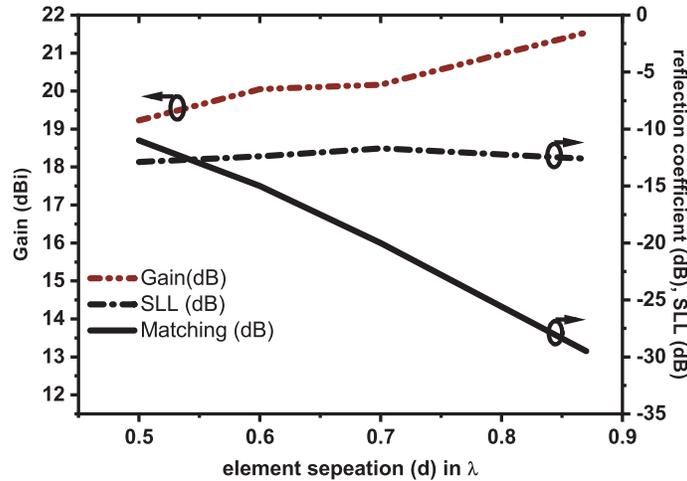


Figure 7. Parametric study of the antenna characteristics with element spacing.

separation which overcomes mutual coupling that deteriorates well-matched element model and feeding network characteristics, for array design is obtained from parametric study.

5. ANTENNA ARRAY FABRICATION & RESULT

The fabricated antenna model is shown in Figure 8. It is a 16 element stack microstrip patch antenna array of same dimension as of simulation model ($295 \text{ mm} \times 30 \text{ mm}$ ($14\lambda \times 1.425\lambda$)) in which the stack patch is supported with 1.7 mm thick rohacell foam material of $\epsilon_r = 1.07$, $\tan \delta = 0.0041$ at 10 GHz. The feeding to the compact meandering stripline feeding network is provided through an SMA connector connected from the bottom side. Stripline to microstrip line transition is utilized for convenient connection of SMA connector to stripline feeding network from bottom side. In order to support the bottom feed, there is also base support made of aluminum for the antenna. The base support is as thick as the length of Teflon material ($= 3.16 \text{ mm}$) in the SMA connector.

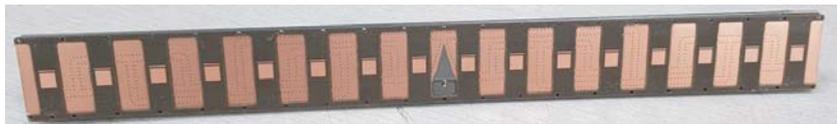


Figure 8. Fabricated antenna array model.

The simulated and measured results of the designed and fabricated model are shown in Figures 9(a) and 9(b). The reflection coefficient comparison plot, Figure 9(a), shows that the measured antenna array S_{11} pattern is in close match to simulated S_{11} plot. The measured S_{11} is -30 dB around the center frequency and below -24 dB in $14\text{--}14.5 \text{ GHz}$ range. There is good agreement for -10 dB impedance bandwidth between measured and simulated results. The far-field radiation plot, shown in Figure 9(b), also shows a good match between simulated and measured results. The gain of the antenna array achieved is $> 20 \text{ dBi}$ with sidelobe level $> 12.5 \text{ dB}$. The expected gain of the 16 element array from the single element result is about 21.6 dBi (analytical) whereas the simulated gain of the array obtained is 21.5 dBi , and the measured gain is about 20 dBi . There are possible causes for mismatch in the simulated and measured results. The proposed design is very compact and consists of multi-layers of dielectric. The bonding material available and used for the multilayer stacking has $\epsilon_r = 2.35$, which is different from antenna substrate permittivity. Also fabrication tolerance could lead to fabrication error. A sensitivity analysis is presented in Figure 10, where reflection coefficient plot of the 16 element array

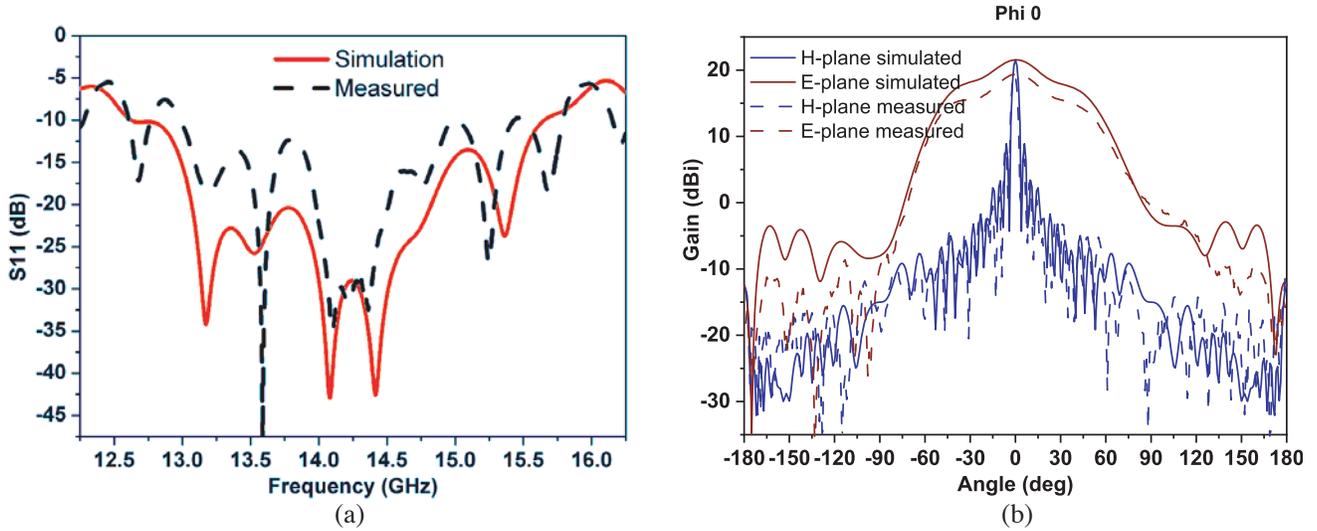


Figure 9. Simulated and measured 16 element stack patch antenna array characteristics (a) Return loss plot, and (b) E/H plane radiation pattern.

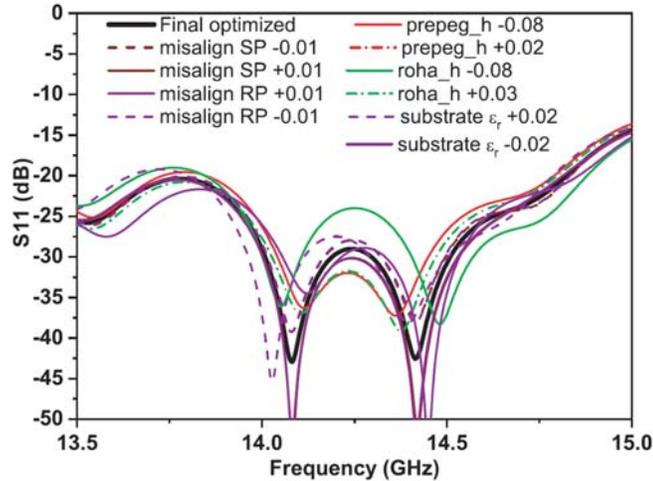


Figure 10. Sensitivity analysis of array model.

is shown with small variation in certain parameters that are more prone to change during fabrication. Sensitivity analysis is performed with bonding material thickness (prepeg_h), rohacell thickness (roha_h), substrate permittivity (ϵ_r), misalignment of resonator patch layer (misalign RP), and misalignment of stack patch layer (misalign SP). The parameter variation is in mm. The rohacell thickness is found to affect the array performance more than others which implies that the gap between resonator patch and stack patch is critical.

Table 1 shows the comparison of the proposed antenna with similar reported Ku-band antenna work. Our antenna model is designed to work for 500 MHz band (14–14.5 GHz); therefore, reflection coefficient value (S_{11}) is tabulated for minimum reflection coefficient over 500 MHz band in cited work irrespective of frequency. Antenna array gain (AG) of the respective cited work along with prototype dimension in λ , number of elements of the array, single element gain (SEG), and sidelobe level (SLL) is also listed in the Table 1 for comparison. Our antenna designed has lower return loss for 500 MHz band and higher element gain and array gain than recently published work.

Table 1. Comparison of present work with similar works.

	Freq. (GHz)	S_{11} (dB)	AG (dBi)	$(L \times W)$ $(\lambda \times \lambda)$	Array element	SEG (dBi)	SLL (dB)
[11]	14.2–14.7	–15	12.5	3.2×3.2	2×2	8.55	NA
[25]	14–14.5	–22	17.5	9.12×1.14	1×8	NA	9.4
[26]	12.1–12.6	–20	20.6	4.48×4.48	4×4	8	12.5
[27]	13–13.5	–20	15.8	2.3×2.3	4×4	6	12.5
[28]	16–16.5	–15	20.25	11.7×1.77	2×16	7.2	10.3
[29]	13.75–14.25	–20	18.5	7×2.43	2×8	10	12
Proposed	14–14.5	–30	21.5	14×1.425	1×16	9.6	12.5

NA — data not mentioned.

6. CONCLUSION

An imperative wideband, high return loss, highly efficient and low-profile 16 element microstrip patch antenna array is designed and fabricated. A careful choice of antenna type (stack patch), substrate material (low loss Taconic TLY5), feeding approach (corporate feeding), and feeding technique (aperture coupled feeding) is adopted in the design of the array for target characteristics at Ku-band frequency range. The matching of the antenna is improved with reactive loading of a u-slit on the resonator patch. The designed single antenna element has a high gain of 9.6 dBi, and the designed 16 element array has a high gain of > 20 dBi. The stripline feeding network developed also complements the antenna element with low return loss. A stripline feeding with metal post is found very appropriate for low loss and compact feeding network design. The feeding network loss of the array is only 0.5 dB which is very low. The antenna element design and the 16 element array developed both have very low reflection coefficient over the target band of 14–14.5 GHz. Compared to recent antenna designs, our designed antenna has higher gain and lower reflection coefficient for 500 MHz bandwidth in Ku-band. Ku band has been adopted in radar systems of many military applications like missile guidance system, SAR, and small drone detection. The developed antenna array with low profile and high performance could be suitable for any such high-end application.

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