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A Single-Layer Broadband Reflectarray in K-Band Using Cross-Loop Slotted Patch Elements

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ABSTRACT A broadband linearly polarized reflectarray antenna is designed by modifying a typically narrowband square patch unit element with cross-loop slot (CLS). Due to the introduction of the CLS, the unit patch element becomes multi-resonant and miniaturized. Besides, the outer length and width of the CLS are one-to-one related to the length of the patch. As a result, more than 480° phase range with quite good linearity is achieved. In addition, the phase ranges are almost parallel to each other from 22.5-26.5 GHz, which signifies its broadband property. Using such 36 × 36 CLS patches in a square aperture of 180 mm × 180 mm size, an offset-fed reflectarray is constructed for an off-broadside radiation pattern. A prototype has been fabricated to experimentally validate the numerical results obtained using CST full-wave simulations. The measurement results exhibit a broad 1-dB gain bandwidth of 17.6% (22.44-26.78 GHz) and a peak gain of 32.2 dBi with an aperture efficiency of 60.6%. Moreover, both the cross-pol and side-lobe levels (SLLs) remain more than 40 dB and 21 dB, respectively, below the peak co-pol level throughout the 1-dB gain bandwidth. The proposed reflectarray can be used as a CubeSat antenna for K-band inter-satellite links (ISL).

INDEX TERMS Aperture efficiency, bandwidth, CubeSat, gain, reflectarray.

I. INTRODUCTION

Reflectarray antenna, which offers various merits, such as high gain similar to the curved reflector, and low-profile and low-mass of the printed array, is now becoming an attractive choice for long range communications [1], [2]. The reflectarray aperture can be printed on thin and small PCB panels, and assembled together during deployment. Due to this advantage, it has been considered as a good candidate for mid- or high-gain antennas of CubeSats [3]. Recently, CubeSats have attracted the industry attention and initiative to form constellation at low earth orbit (LEO) to attain seamless connectivity across the globe through the internet of things (IoT) [4]. Towards this goal, reflectarray antenna can be useful to enable inter-satellite links (ISL) between individual CubeSats to reduce the signal latency [5], [6]. Three channels in K-band, 23.15-23.55 GHz, 24.45-24.75 GHz, and 25.25-25.55 GHz, are allocated for such ISL applications [7].

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The reflectarray antenna for ISL should cover all these three channels. However, a major drawback of reflectarray antennas is their narrowband performance due to the inherent narrowband response of microstrip elements [2], [8] and the differential spatial phase delay resulting from different path lengths from feed to each element on the aperture [9].

A number of different techniques are proposed in the literature to improve the bandwidth of reflectarray antennas. In [10], [11], stacked patches of variable size in multilayer configuration are used to increase the reflectarray bandwidth. For larger reflectarray, phase delay lines aperture-coupled to patches are used [12]. However, the above multilayer configurations create problems, such as increased weight, additional fabrication cost and complexity, etc.

Therefore, various efforts have been made to achieve broadband reflectarray in single layer configuration. It is shown that a subwavelength element [13], [14] or a multi-resonant element [15], [16] can provide broad bandwidth in single layer. The phase delay lines which are aperture coupled to the patches on different layer [12], are connected to the

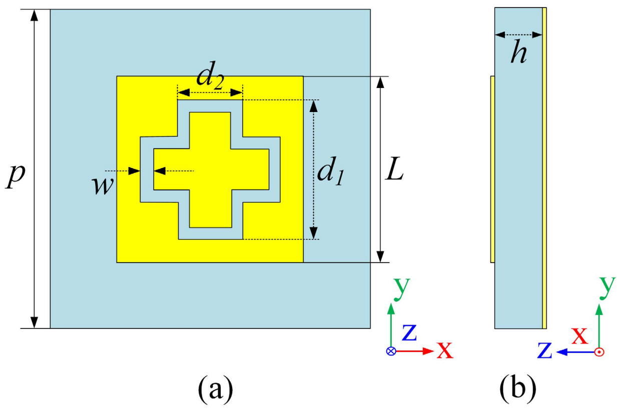

FIGURE 1. Geometry of the proposed phasing element for broadband reflectarray antenna: (a) Top view. (b) Side view. (Design parameters of the phasing element: $p = 5$ mm, $h = 1.52$ mm, $w = 0.2$ mm, $L = 1.5$ to 4.6 mm, $d_1 = k_1 \times L$, $d_2 = k_2 \times L$, $k_1 = 0.8$, $k_2 = 0.35$).

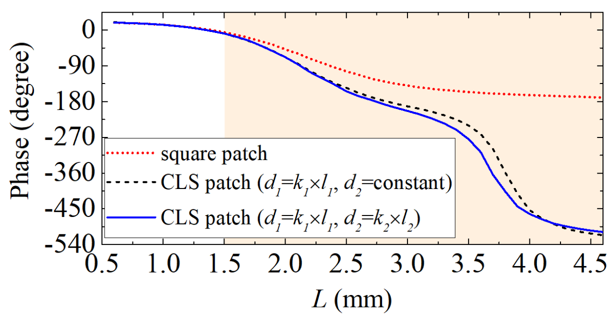

FIGURE 2. Reflection phase with respect to the change in length (L) in the evolution of the proposed CLS patch under normal incidence of y-polarized wave at 24.6 GHz. Here, d_2 is considered as 0.6 mm when it is kept constant.

elements on the same layer in [17]–[19] to achieve broad 1-dB gain bandwidth. In [20], a dielectric metamaterial-based broadband design is shown, whereas polarization rotating elements are employed in [21]. Broad bandwidth is also achieved using different phase synthesis methods [11], [15], [22]. However, it is worth mentioning that the above single layer reflectarrays have certain undesirable characteristics. The subwavelength element based broadband reflectarray often use thicker substrate to attain phase range close to 360^0 [13]. Both the multi-resonant and polarization rotating element based broadband reflectarrays usually use complex geometrical configurations, which require time-consuming numerical simulations of the unit cell element to determine its optimum response. Moreover, most of the available phase synthesis techniques of single layer reflectarray reduce the peak gain at the cost of the improved bandwidth. Recently, reflective reconfigurable and programmable metasurfaces have aroused great research interest due to easy fabrication, low cost, and multiple functionalities, such as EM wave radiation and beam scanning, scattering manipulation, polarization conversion, etc. [23], [24]. However, such metasurfaces for EM wave radiation and beam scanning with broad 1-dB gain bandwidth

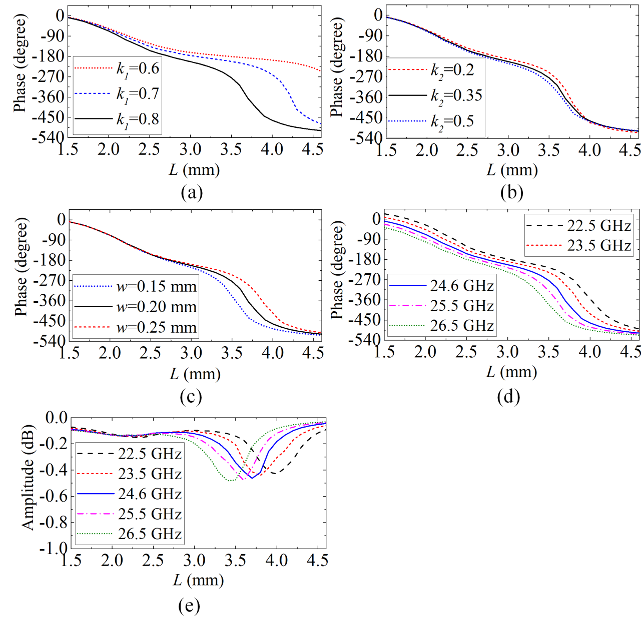

FIGURE 3. Reflection phase with respect to the variation of the key design parameters of the unit cell: (a) k_1 variable, (b) k_2 variable, (c) w variable. (d) Reflection phases and (e) amplitudes for different values of frequency under normal incidence of y-polarized wave.

has been rarely reported and it still requires a significant research attention.

In this paper, a novel single layer unit cell is proposed as phasing element for a broadband reflectarray. By inscribing a cross-loop type slot, a typically narrowband patch is converted into a broadband phasing element. The 1-dB gain bandwidth of the proposed reflectarray (17.6%, 22.44-26.78 GHz) can cover the three channels in K-band, allocated for CubeSat ISL [7]. As compared to most of the broadband designs [16]–[18], the proposed reflectarry doesn't use any additional air layer. Moreover, the reflectarray exhibits significantly low cross-pol and side-lobe levels (SLLs) as compared to the reported works.

II. DESIGN AND ANALYSIS OF THE PHASING ELEMENT

The unit element configuration of the proposed broadband reflectarray is shown in Fig. 1. The CLS square patch is printed on the top of a ground-backed Roger RO4003C ($\varepsilon_r = 3.55$, tan $\delta = 0.0027$) substrate of thickness $h = 1.52$ mm. To avoid grating lobes and obtain improved 1-dB gain bandwidth [13], a periodicity $p = 5.0$ mm ($0.41\lambda_0$ at 24.6 GHz) is set for the unit cell. The outer length (d_1) and width (d_2) of the CLS are one-to one related with the variable length (L) of the patch as $d_1 = k_1 \times L$ and $d_2 = k_2 \times L$, respectively. With a comprehensive parametric study provided in this section, the range of variable L, and the constants k_1, k_2, and w of the phasing element are determined with a view to achieve maximum phase range, phase linearity and parallel phase responses in a broad frequency range, simultaneously. CST MWS with unit cell boundary conditions and Floquet

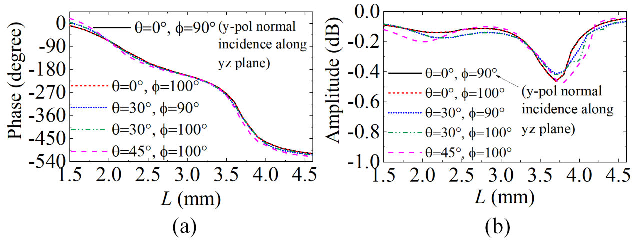

FIGURE 4. (a) Reflection phase behavior with respect to the change in incidence angle. (b) Amplitude of the reflection coefficient with respect to the variation in incidence angle.

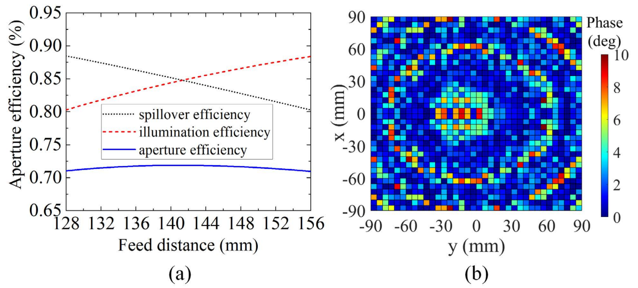

FIGURE 5. (a) Variation of efficiencies with feed height. (b) Phase error distribution on the realized reflectarray aperture at 24.6 GHz.

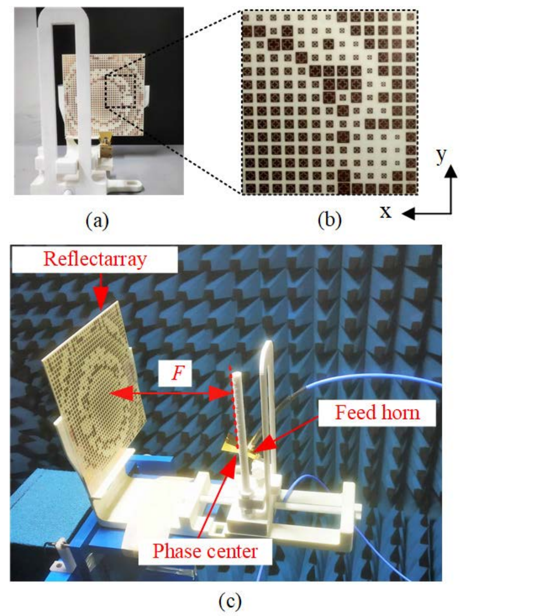

FIGURE 6. (a) Photograph of the fabricated reflectarray sample along with its feeding assembly. (b) An enlarged portion of the fabricated reflectarray. (c) Measurement set up inside the anechoic chamber.

mode excitations is used for the numerical investigations of the phasing element.

The CLS patch, mentioned above, is evolved from a classic square patch element. The reflection phases as a function of length of the patch in the evolution of the proposed element are plotted in Fig. 2 for a y-polarized normal incident plane wave at 24.6 GHz. From Fig. 2, it is evident that the modified squared patch with CLS can provide more than 480^0 phase variation. When both the degrees of freedom are variable, the phase linearity has also improved which helps to attain low phase error distribution on the reflectarray aperture. It should be noted that when $L < 1.5$ mm, the structural parameters of the elements are not realizable with regard to the manufacturing accuracy of our fabrication technology. Therefore, in our design, L will be varied from 1.5 mm to 4.6 mm.

The reflection phase behavior for the variation of k_1, k_2 and w is shown in Fig. 3. It is evident that the increment of k_1 significantly influences to improve the phase range. Moreover, quite reasonable linearity is observed in the phase response for $k_1 = 0.8$. The variation of k_2 doesn't affect the phase response much. It can slightly improve the phase linearity. It should also be observed that when w is decreased, the phase linearity improves. The final parameters, which provide optimum phase range and phase linearity while ensuring the fabrication feasibility, are given in Fig. 1. The reflection phase response over a frequency range of 22.5–26.5 GHz is shown in Fig. 3(d). It can be observed that the phase responses have overall quite good linearity though around 3.5 mm they are slightly nonlinear. Moreover, the phase responses at different frequencies are almost parallel to each other. This signifies the broadband property of the CLS patch element. The amplitude responses with respect to the variation of frequency have also been plotted in Fig. 3 (e). It can be observed that proposed phasing element provides very low reflection loss over a broad bandwidth. The reflection loss is higher at the second resonance. It slowly increases as the frequency is increased. The observed maximum reflection loss is 0.486 dB at 26.5 GHz for a normal incident wave.

The behavior of the CLS patch is studied for the change in incident angle of the y-polarized waves up to 45^0. From Fig. 4 (a) it can be observed that the reflected phase curve variations are insignificant for change in oblique incidence (θ) and polarization angle (ϕ). It can be observed from Fig. 4 (b) that maximum element loss remains considerably low for change in incidence angles even though Roger RO4003C substrate with $\tan\delta = 0.0027$ is used. The maximum reflection loss is -0.46 dB for 0^0 and -0.48 dB at 45^0, respectively. Therefore, from Fig. 4 it is clear that the proposed element can provide almost unchanged phase response and minimum reflection loss for variation in the incidence angle.

III. CONSTRUCTION OF THE REFLECTARRAY PROTOTYPE

The above-studied CLS patch is used to construct the reflectarray with an offset feed at $\theta_F = -27^0$, $\phi_F = -90^0$ for an off-broadside reflected beam towards $\theta = 23^0$, $\phi = 90^0$. Thus, the feed blockage can be avoided. A total of 36×36 CLS patch elements are used on an aperture size of 180 mm $\times$ 180 mm ($14.76\lambda_0 \times 14.76\lambda_0$). The measured value of q in the $\cos^q(\theta)$ pattern of feed horn at 24.6 GHz is $q = 6$. With the above parameters, the distance from the phase center of the feed to the reflectarray is calculated as $F = 142$ mm

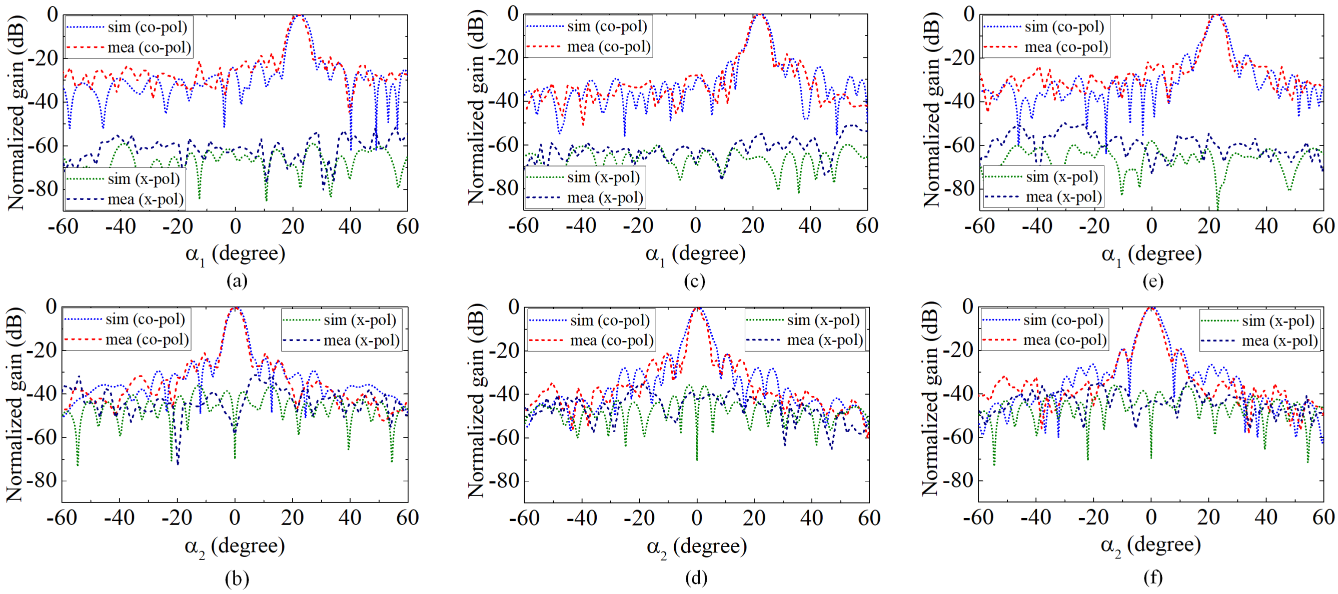

FIGURE 7. Simulated and measured normalized radiation patterns of the proposed reflectarray for both the α_1 (top row) and α_2 (bottom row) planes at (a)-(b) 22.5 GHz, (c)-(d) 24.6 GHz and (e)-(f) 26.5 GHz, respectively.

for the edge illumination level below −10 dB and maximum aperture efficiency [25], as shown in Fig. 5(a).

The appropriate element at each unit cell on the reflectarray aperture is determined by minimizing the error between the theoretical phase [26] at that location and the achievable phase as a function of length. An objective function for minimizing the phase errors is defined as

$$obj_{mn}(L) = \left|\varphi_{mn,desired} - \varphi_{mn,achievable}(L)\right| \quad (1)$$

where $obj_{mn}(L)$ is the objective function to find out L corresponding to the minimum phase error at mn^{th} location, $\varphi_{mn,desired}$ is the desired phase delay at mn^{th} location, and $\varphi_{mn,achievable}(L)$ is the achievable phase delay obtained from CST unit cell simulation, respectively. The optimum element at the mn^{th} location can be obtained by finding its corresponding L by minimizing the objective function as $\min(obj_{mn}(L))$ such that $1.5mm \le L \le 4.6mm$. The minimum phase error distribution, thus achieved using MATLAB at 24.6 GHz, is shown in Fig. 5(b). It can be seen that phase error does not exceed 10^0 at any location. However, it is observed that the maximum phase error value increases but remains within an acceptable limit for extreme frequencies of the 1-dB gain-bandwidth.

IV. RESULTS AND DISCUSSION

The full-wave simulation of the above reflectarray configuration is carried out in CST MWS using the integral equation (IE) solver. In this solver, the radiation characteristics of the offset feeding horn at different frequencies are provided by importing them as a far-field source from the results where the feed horn antenna is separately simulated in transient solver (TS) with wave-port excitation. To experimentally validate the full-wave simulated results, the proposed reflectarray design is fabricated. A photograph of the fabricated sample along with its feeding arrangement is shown in Fig. 6(a) and (b). A 3-D printed supporting arm made of low-permittivity PLA plastic ($\varepsilon_r \approx 2.4$) is used for the reflectarray-feed assembly. The experimental measurements are carried out inside the anechoic chamber. A photograph of the experimental setup is shown in Fig. 6(c).

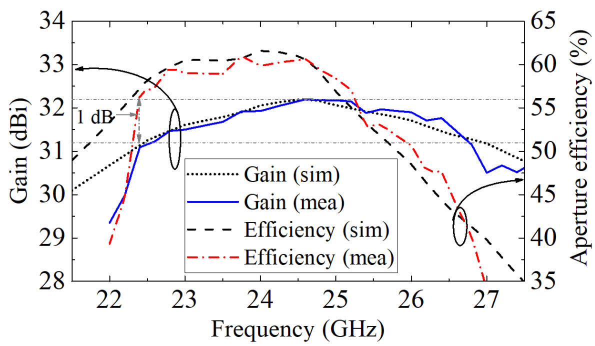

FIGURE 8. Simulated and measured realized peak gain and aperture efficiency of the proposed reflectarray.

The numerically simulated and experimentally measured radiation patterns of the proposed reflectarray are shown in Fig. 7. The normalized radiation patterns for both the α_1 and α_2 planes are plotted for three frequencies, 22.5 GHz, 24.6 GHz and 26.5 GHz, respectively. The measured radiation patterns show good agreement with the full-wave simulated results. From the measured results, it can be observed that the main beam is directed towards the desired 23^0 and 0^0 in the α_1 and α_2 plane, respectively for all the frequencies. Moreover, the SLLs and cross pol levels are minimum 21 dB

TABLE 1. Comparison with other single-layer broadband reflectarray antennas.

Ref.	Frequency (GHz)	Radiated Beam Direction	Thickness (λ_0)	Additional Air Layer	1-dB Gain Bandwidth (%)	Peak Gain (dBi)	Max Aperture Efficiency (%)	Cross Pol Level (dB)	Side Lobe Level (SLL) (dB)
[14]	10	Broadside	0.11	No	18†	28.2	56.5	<-30	-12
[15]	12	OB**	0.13	No	30	31.6	NR*	NR*	-18
[16]	13.5	OB**	0.17	Yes	17	30.8	66	NR*	NR*
[17]	8.5	OB**	0.08	Yes	16.5	24.6	59	<-25	-20
[18]	10	OB**	0.09	Yes	31.5	25.8	50	<-26	-20
[19]	10	OB**	0.106	No	30	25.0	58.3	<-32	-17.5
[20]	13.5	Broadside	0.54	No	18.1	30.3	45.6	NR*	-10.7
Our Work	**24.6**	**OB****	**0.12**	**No**	**17.6**	**32.2**	**60.6**	**<-40**	**-21**

**OB=off-broadside †bandwidth for 1.5 dB gain *NR=not reported

and 40 dB below the main lobe maximum for all the frequencies. The proposed reflectarray produces low cross-pol levels due to its four-fold rotational symmetric unit elements as well as the y-polarized wave incidence along the $\phi = 90^0$ plane. Slight discrepancies can be observed in the measured results, which appear mainly due to the fabrication tolerance of the reflectarray and its installation error with the feed during the measurements.

The simulated and measured gain of the proposed reflectarray with respect to the change in frequency are plotted in Fig. 8. It can be observed that the measured values of the peak gain agree well with the simulated results. The reflectarray provides maximum measured gain of 32.2 dBi at 24.6 GHz. The level of the gain doesn't drop below 1 dB from the maximum gain in the frequency range from 22.44 GHz to 26.78 GHz. Thus, a broad 1-dB gain bandwidth of 17.6% is achieved covering all the three channels allocated for K-band CubeSat ISL. The antenna aperture efficiency is calculated from the realized gain (G) and physical aperture area (A) using $\eta_a = G_{abs}\lambda^2 / 4\pi A$ and plotted in Fig. 8. It can be observed that the maximum aperture efficiency reaches to 60.6% despite the presence of the reflection loss (maximum level reaches up to 0.48 dB) (Fig. 4(b)) due to the loss tangent ($\tan\delta = 0.0027$) of the Roger RO4003C substrate. The performance of the proposed reflectarray is compared with the available state-of-the-art reflectarrays in Table 1. It can be observed that the proposed reflectarray works at higher operating frequency as compared to all the listed broadband reflectarrays. It doesn't require any additional air layer as compared to [16]–[18]. Its thickness is lower than [15], [16], [20] and comparable to the other reported works without the air layer. Moreover, the reflectarray design can provide lower cross-pol and SLL as compared to all the reported works. From Table 1, it is also apparent that our proposed reflectarray shows a good trade-off between the 1-dB gain bandwidth, peak gain, aperture efficiency, SLL and cross-pol level.

V. CONCLUSION

A broadband reflectarray is designed with a 1-dB gain bandwidth of 17.6% from 22.44-26.78 GHz. The broad bandwidth is achieved by modifying a typically narrowband square patch unit element with a cross-loop slot (CLS). The reflectarray produces off-broadside radiated beam from an offset feed so that it can be easily deployed for ISL in a CubeSat constellation. From the measured radiation patterns, gain, aperture efficiency, side-lobe and cross-pol levels, it can be concluded that the proposed reflectarray is a good candidate for the K-band CubeSat ISL.

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