Miniaturized Microstrip Reflectarray Antenna Design for Ku-Band Applications

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Abstract

The main objective of designing a Microstrip Reflectarray Antenna is to exploit for the Ku-Band, Designing parameters concentrates on the phase and bandwidth. Development and wide usage of communication through the wireless media gives an opportunity for the research and development of small antennas. Such an antenna is deployable at the base stations as well as on to the satellites. Hence, miniaturization is one of the important requirements. The paper reviews the phase response of the reflectarray antenna to achieve a planar wave front, techniques to improve the bandwidth as well as for miniaturization of microstrip reflectarray antenna.

1. Introduction

In the middle of last century, the discovery of parabolic antenna revolutionized various applications in almost all walks of life. The parabolic reflector is common to most satellite antenna designs because of its ability to collimate an incident spherical wave. Although parabolic reflector antennas are high-gain antennas and efficient radiators, they found to be bulky in size and large in weight, because of their curved reflecting surfaces.

Shaped reflector antennas have become common on communications satellites because of their physical simplicity. Due to 3-D shape they require a considerable volume, which is unwelcome in satellite applications. Due to these reasons, efforts have been made to replace parabolic and shaped reflector antennas by their planar equivalents, which can be made of large size using the flat panel assembling approach. As a result reflectarray is used to solve the problems associated with the parabolic or conventional array antennas.

The term 'flat reflector' utilizes both technologies of reflector and array hence also called as the Reflectarray. The reflectarray antenna [1-4] is consisting of a slightly curved or flat surface as a reflector with an illuminating feed antenna. On the reflecting surface, array of each element is designed in such a manner to scatter the incident field with proper phase and they are required to form a coherent beam in the desired direction. Even though the theory of reflectarray is not new, the fast development in microstrip antenna technology has escort to the development of an innovative flat reflector antenna i.e. Microstrip Reflectarray antenna.

Microstrip or printed reflectarray has several advantages over conventional reflectarray, especially for the space applications, which are as follows, First, microstrip reflectarrays are compact thus it saves the volume for launch due to their flat structure. Second, as the structure is reduced to a single flat sandwich thus simplifies the mechanical design [2, 3]. Third, due to its simpler and reliable folding mechanism compared to parabolic reflector antenna it can be easily installed on spacecrafts. Fourth, using simple photo-etching technique, a low cost microstrip reflectarray antenna can be fabricated. Fifth, in a reflectarray the large number of element have an ability to adjust the phase, thus it gives a very accurate contour beam shape with phase-only synthesis technique.

C-band was the first band to be used for satellite communication systems. However, the band became overloaded due to the same frequency being used by terrestrial microwave links. Thus, satellites were constructed for the Ku-band or Kurz-under Band. Ku-band is entirely used by satellite communication systems, thus interference with the microwave systems is totally eliminated. It is referred from [31].

The main part in designing is to achieve a planar wave front of a reflectarray antenna. Section IIof phase synthesis shows the methods and results of getting phase of each element for the planar wave front. One of the major drawbacks of microstrip reflectarray antenna is its limited bandwidth. Section III shows techniques to improve the bandwidth of microstrip reflectarray antenna. Section IV includes the miniaturization techniques to be applied on to the microstrip reflectarray antenna.

2. Numerical Aspect

Consider a Reflectarray with elements located in the rectangular grid with a spacing of dx on x-axis and dy on y-axis. The position of Reflectarray and feed are offset, in global coordinate axis. It is to be referred form references [5,6].

The basic design principle requires that the phaseψ_{mn} of the field reflected from an element in the Reflectarray be chosen so that the total phase delay from the feed to a fixed aperture plane in front of Reflectarray is constant for all elements.

For the beam to be focused at the desired direction($\hat{r}_0, \theta_0, \phi_0$), the key design equation is the equal phase delay condition given by [6]

$$k_0\left(\vec{R}_{mn}+\vec{r}_{mn}.\hat{r}_0\right)-\psi_{mn}=2\pi N \quad \text{.................. (1)}$$

Where $\vec{R}_{mn}$ is the distance from the feed to mnth array element $\vec{r}_{mn}$ is the position vector from the center ofthe array to the mnth element and $\hat{r}_0$ is the unit vector in the direction of main beam of Reflectarray. The resonant length of mnth patch element or the stub of patch is then selected to produce a phase shift ψ_{mn} in the field reflected from the element [7,8]. These parameters are shown in Figure 1.

The feed is located at distance f away from the centre of Reflectarray and the coordinates of mn[th] patch.

$$\vec{r}_{mn}=x_{mn}.\hat{x}+y_{mn}.\hat{y} \quad \text{.......................... (2a)}$$

$$\vec{R}_{mn}=\sqrt{x_{mn}^2+y_{mn}^2+f^2} \quad \text{.................. (2b)}$$

$$\hat{r}_0=\sin\theta_0\cos\phi_0\hat{x}+\sin\theta_0\sin\phi_0\hat{y}+\cos\theta_0\hat{z} \quad \text{(2c)}$$

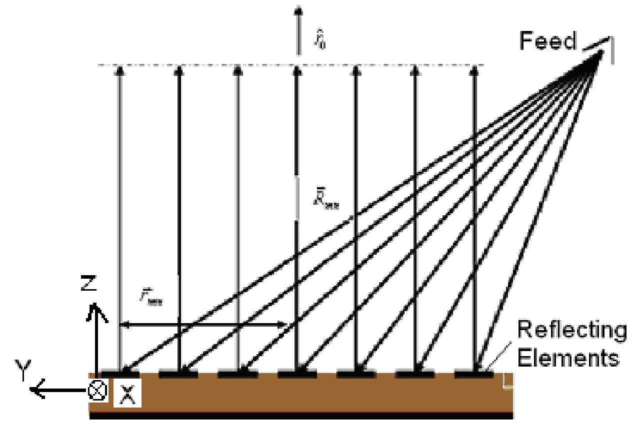

Figure 1: Microstrip Reflectarray element design [5].

The array factor of the reflectarray antenna is given as

$$AF(\theta,\phi)=\sum_m\sum_n I_{mn}e^{jk_0\left(\overrightarrow{r_{mn}}.\hat{r}\right)} \quad \text{.................. (3)}$$

$$I_{mn}=(e^{-jkR_{mn}}.e^{j\psi_{mn}}.\cos^q\theta_{mn})/R_{mn} \quad \text{...........(4)}$$

where I_{mn} is the element excitation. It can be calculated by considering the distance from feed horn to mnth element as well as the phase of each element.

The product of array factor and element pattern computes the electric field pattern.

$$E(\theta,\phi)=AF(\theta,\phi)\cdot\cos^q\theta \quad \text{.................. (5)}$$

The directivity is then computed [7], using the power pattern $P(\theta,\phi)$ of the electric field $E(\theta,\phi)$. Directivity is the ratio of radiation intensity in a given direction from antenna to the radiation intensity averaged over all directions.

$$D(\theta_0,\phi_0)=\frac{4\pi P(\theta_0,\phi_0)}{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi/2}P(\theta,\phi).\sin\theta d\theta d\phi} \quad \text{........ (6)}$$

3. Phase synthesis technique

The reflectarray antenna [1-4] is consisting of a slightly curved or flat surface as a reflector with an illuminating feed antenna. On the reflecting surface, array of each element is designed in such a manner to scatter the incident field with proper phase

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and they are required to form a coherent beam in the desired direction as shown in figure [1].

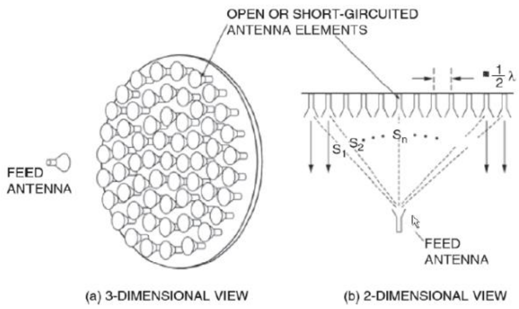


Figure 2: Configuration of a Reflectarray antenna [4]

A suitable phasing method is used for a reflectarray antenna to convert the spherical waves coming from feed into the plane waves. The phase of reflected plane wave of given polarization of the incident wave determines the phasing characteristics of an individual array element. The problem of phase determination can be achieved by assuming identical elements as a unit cell problem, where the element is placed inside a rectangular waveguide short circuited at one end. The angle of incidence of plane wave is determined by the selection of walls of rectangular waveguide. For a horizontally polarized normal incident wave, the top and bottom walls are acting as perfect magnetic conductor and side walls as a perfect electric conductor.Using this approach, the essential phase is resolved as the phase of reflected plane wave of TEM wave passing through the waveguide. Thus to achieve the phasing characteristics, dimensions of the patches are to be adjusted in such a way so as to get the resultant phase difference of360°.

The feed antenna spatially illuminates the elements to form a planar phase front in the far-field region. In other words, the phase of each element is pre-designed so as to compensate for the different phases associated with the different path lengths, variable patch size, and angular rotation of different patch element [4].

Use of variable length delay lines is to adjust the phase difference of the incoming signal from feed. This resultant reflected signal provides the direction of main beam. The signal can also be gathered from the free space and send to the feed antenna; hence the reflectarray antenna can be used as a transmitter and receiver.

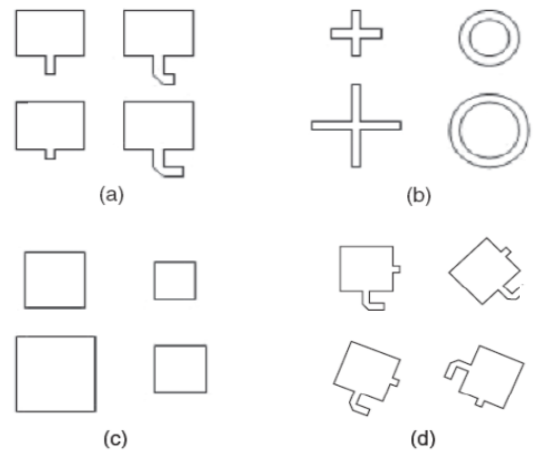


Figure 3: Various reflectarray elements, (a) identical patches with variable –length phase delay lines, (b) variable-size dipoles or loops, (c) variable-size patches, (d) variable angular rotations [4].

The patches with variable angular rotations and straight and bent delay lines are used to improve the gain and bandwidth of the reflectarray antenna.

To become familiar with the standard design, several factors are considered in the practical design of microstrip reflectarray antenna such as gain, patch size, bandwidth or efficiency. These factors include: (1) reflecting board material, (2) elements dimensions, and (3) arrangement of elements.

The use of lower value of substrate dielectric constant increases each element space than that of higher dielectric constant. Following figure shows that reflection phase difference is 360° for the lower and higher value of dielectric constants [9].

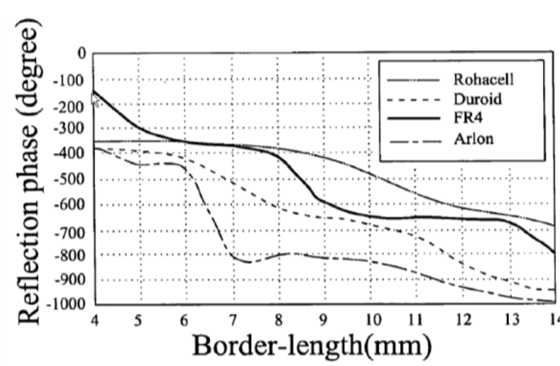


Figure 4: Reflection phase at 11 GHz Versus border-length of the antenna patch in different materials [9].

Incremental phase change is achieved in [10] by controlling length of patch and slot over a Bandwidth of 4% for Ku-Band. The result is shown in figure 5.

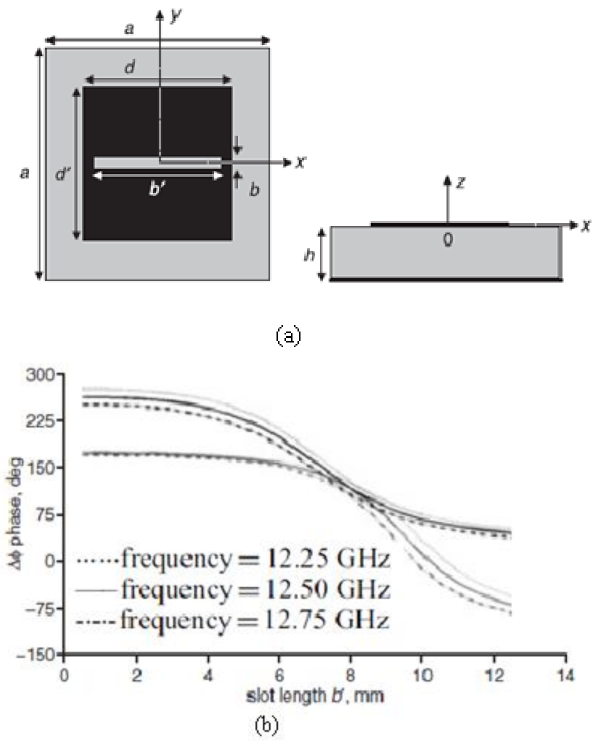
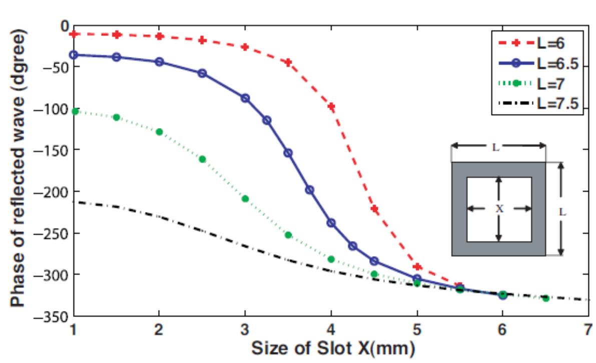
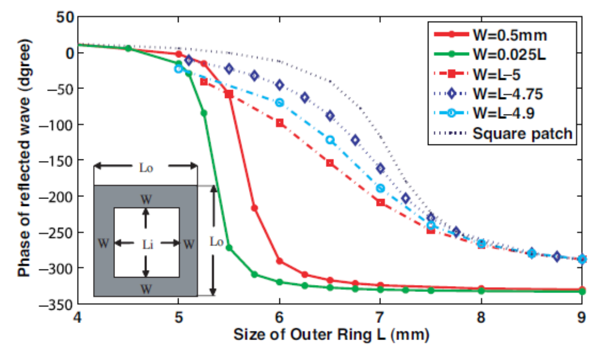


Figure5: (a) Geometry of patch loaded with slot (b) phase variations against slot length. [10]

In order to obtain a good phase response, a new technique of varying only one dimension of elements is investigated. This investigation observes that there is a slower variation and a smaller slope for the phase response is achieved. The better phase response is obtain by using a square and circular rings [11] rather than dipoles and patches. Figure 6 shows that when one of the dimension of square ring i.e. either outer side or inner side is scaled-up or scaled-down it results in the net reduction in the slope of phase as well as phase range from 0 to 360°.



(a)



(b)

Figure6: Phase response (a) of fixed-size (L) square patches against slot size(X) (b) for square rings against outer size (L) for various schemes of varying the width W [11].

4. Bandwidth Enhancement Technique

An application of reflectarray antenna is found in satellite communication, contoured beam space antennas, radar and commercial usages. As compared to the advantages of reflectarray antenna based on electrical properties over parabolic reflector antenna, it suffers from a major drawback of limited bandwidth capability [12].

The bandwidth of microstrip reflectarray is better when compared with planar array but it is inferior when it is compared with reflector antennas. The two prime factors responsible for the limitation of bandwidth are (1) individual microstrip patch element bandwidth and (2) differential spatial phase delay.

First limitation can be overcome by stacking multiple patches [13-18]. The table below shows the comparison of the single and double layer reflectarrays. The comparison shows that larger bandwidth is obtained with the double layer reflectarray structure.

Table I: Comparison of Single and Double Layer Reflectarrays

	Reflectarray in [19]	Reflectarray in [20]
Central frequency (GHz)	9.075	11.95
Frequency Band (GHz)	8.85-9.5	11 – 13
Frequency Band (%)	7.2	16.7
Polarization	Dual linear	Dual linear
F/D	0.87	0.84

Second limitation of bandwidth of microstrip reflectarray antenna can be overcome by reducing frequency excursion error which is generated due to different path length of each element from feed point on the wave-front of radiated beam. But it limits the size of the reflectarray. The use of globally curved aperture with piece-wise flat structure gives good bandwidth. Variable patch size reflectarray governs a major parameter to improve the bandwidth. The use of closely spaced elements reduces the size of aperture as well as improves the bandwidth of the microstrip reflectarray antenna. Table II shows that as the aperture diameter increases the bandwidth decreases [21].

Bandwidth of reflectarray antenna can also be decreased by the selection of suitable dielectric material. Use of lower value of dielectric constant improves the bandwidth. Table below shows the list of materials used for designing an infinite reflectarray at 10 GHz and by changing the reflection loss from 10% to 20%, respective bandwidth is measured.

Table II: Comparison of aperture diameter with bandwidth. [21]

Aperture diameter	Relative bandwidth improvement
10λ	61.63 %
20λ	36.28 %
30λ	22.25 %
40λ	15.47 %

Table III: Combined, dielectric and conductor loss for different materials [22]

Dielectric Material	Dielectric Constant (ε_r)	Loss tangent (Tanδ)	Conductivity of conductor (Copper) σ (Ms/m)	Combined Loss R_l (dB)	Dielectric Loss α_d (dB)	Conductor Loss α_c (dB)
Alumina (95%)	9.75	0.0003	59.6 Ms/m	0.519 dB	0.148 dB	0.370 dB
Beryllia	6.5	0.0004	59.6 Ms/m	0.395 dB	0.138 dB	0.257 dB
CEM	4.5	0.025	59.6 Ms/m	6.875 dB	6.656 dB	0.187 dB
Gallium Arsenide	13	0.006	59.6 Ms/m	4.326 dB	3.831 dB	0.455 dB
Roger 5870	2.33	0.0012	59.6 Ms/m	0.313 dB	0.189 dB	0.122 dB
Roger 5880	2.2	0.0004	59.6 Ms/m	0.178 dB	0.060 dB	0.118 dB
Silicon	11.9	0.004	59.6 Ms/m	2.857 dB	2.406 dB	0.444 dB
Teflon	2.08	0.0004	59.6 Ms/m	0.183 dB	0.063 dB	0.119 dB
Vaseline	2.16	0.001	59.6 Ms/m	0.261 dB	0.146 dB	0.114 dB

It is shown in the above table that materials like CEM and Gallium Arsenide having high loss tangent value gives high combined loss (reflection loss) in which dielectric loss is more as compared to conductor loss, because these materials demonstrate high dielectric absorption in the substrate of reflectarray antenna. The materials like Teflon and Alumina with low loss tangent value gives low reflection (combined) loss. The figure 7 compares bandwidth with the dielectric constants. Bandwidth decreases with increase in the dielectric constant.

One of the simplest methods used to improve the bandwidth of reflectarray antenna is the use of thick substrate in between patch element and ground. The major drawback of increasing thickness of the substrate is it reduces the efficiency [23].This result in increasing spurious feed radiation and surface wave power. For direct radiation, a portion of total available power radiated by patch antenna is trapped along the substrate surface. This trapped power in terms of electromagnetic energy gives surface waves. The surface waves are found to be spread in a cylindrical form across the excitation point where the electric field amplitude decreases with distance. These waves illuminate on ground plane and are reflected back into the substrate. The reflected wave reaches the dielectric air interface, which again reflects them. Following the zigzag path, waves reach the borders of the microstrip structure where they are diffracted by edges giving end-fire radiation.

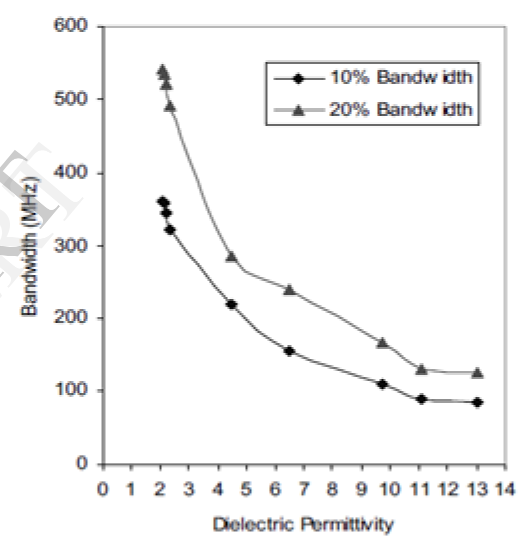


Figure 7: Trend of Bandwidth Performance (22)

5. Miniaturization Techniques

Development and wide usage of communication through the wireless media gives and opportunity for research and development of miniature antennas. Especially for satellite communication, antennas are either loaded on to the satellite or on the base stations. Microstrip reflectarray antenna adds up a greater advantage of light weight, when it is placed on the satellite.

There is a stronger relationship between the antenna size and its performance mainly bandwidth and gain. An antenna size can be determined by the fabrication techniques but by the physical laws. An antenna can give good performance when it is resonant and its size is comparable to the frequency.

Design of reflectarray antenna needs the elemental design first. Thus, miniaturization techniques base on the microstrip patches are as follows:

The total area of patch is minimized by changing it shape and making slots in the ground layer. The design of patch with ground plane contain slots is termed as ground-cut slot technique [24] as shown in figure 8. Compared to the standard rectangular patch antenna, the patch antenna with slot at ground plane as shown in figure below, gives 62.3% reduction in area, having same resonant frequency. This method works with a little control of radiation capability, when accuracy of fabrication and measured error is considered.

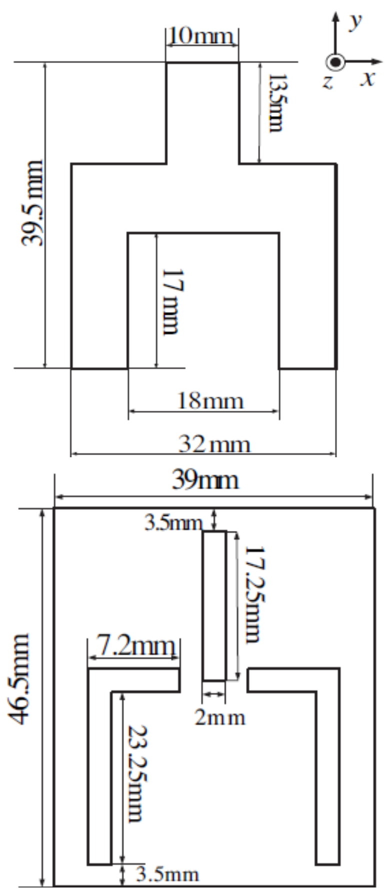


Figure 8: Configuration of Patch and ground plane with ground-cut slot method [24]

When the parallel slotting technique [25] is used on the equilateral triangular patch antenna it gives 37.45% of miniaturization. While the same technique gives 84.73% of miniaturization when it is ground is also slotted with patch. However it reduces the input gain.

Table IV: Simulated Results for Different Structures [25]

Properties	Conventional Equilateral Triangular Patch	Slotted Equilateral Triangular Patch	Equilateral Triangular Patch loaded with slotted
Resonant frequency (GHz)	4.08	3.24	1.6
Return Loss (dB)	-27.49	-29.9	-45.97
VSWR	1.09	1.07	1.01
Gain (dB)	6.98	6.17	2.76
Miniaturization (%)	--	37.45	84.73

A rectangular patch structure provides good radiation when resonant size is half of guide wavelength. The use of mirroring in a conducting wall (like H-Shape) increases the patch length and thus reduces the area of patch. Such technique is applied in shorted microstrip patches with notches and slots, PIFA, Stacked patches and folded monopole antennas. Application of notches and slots in a shorted patch [26] gives 28.5 % size reduction compared to those shorted patches without notches and slots.

Miniaturization can be achieved by adding more electrical length with less volume. This introduces fractal antennas [27,28]. Increasing the fractal dimensions of antenna leads to increase the percentage of miniaturization. The limitation for using such miniaturization technique is the reduction of band, complexity in shape, mathematical calculation, and shift in resonant frequency by a small amount.

Miniaturization can be achieved based on the type of substrate used. Use of Substrate as a reactive impedance surface, minimizes the size with improvement and enhancement of both bandwidth and radiation characteristics [29]. But this needs higher value of the dielectric constant. The use of magneto-dielectric substrate [30] gets better response to the bandwidth and efficiency of antenna, as well as decreases approximately 27% of the antenna patch size. One of the limitations of using magneto-dielectric substrates to antennas is as the permeability value increases it creates strong propagation of surface wave. This can be handled by using Electromagnetic Band Gap Structure or Reactive impedance surface.

6. Conclusion

Although parabolic reflector antennas are high-gain antennas and efficient radiators, they are bulky in size and large in weight. The invention of reflectarray overcomes the disadvantage of parabolic reflector antennas for satellite communication. To eliminate the problem of interference with microwave systems Ku-band is used with frequency range of 12-18 GHz. On the reflecting surface, array of each element is design to form a planar phase front. To achieve the phasing characteristics, dimensions of patches or patch loaded with slots are adjusted in such a manner to get the resultant phase difference of 360°. The major drawback of reflectarray is its limited bandwidth capability. The bandwidth enhancement techniques include multilayer structure, variable patch size, uses of substrate have been considered in the literature. The communication through wireless media gives an opportunity for research and development of miniature antennas. The miniaturization techniques on the microstrip patch antennas have been considered in the literature.

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