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Reflectarray antennas: A review

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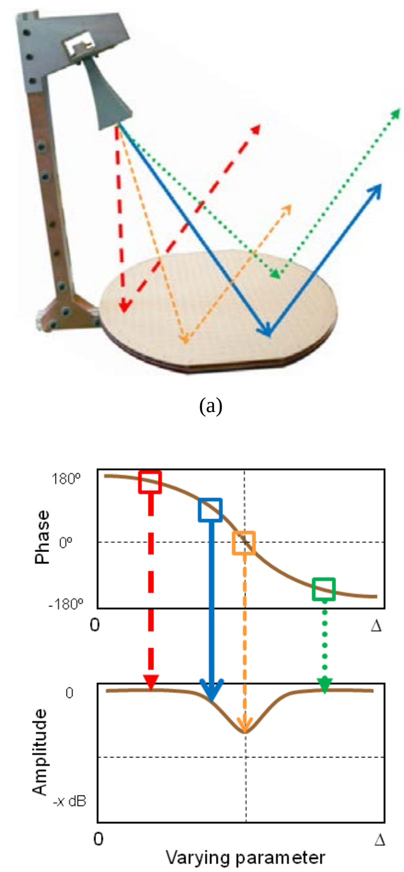
***Abstract*—Reflectarray antennas have attracted special attention for implementing high gain antennas as they combine some advantages of phased arrays and reflectors, such as low losses, ease of manufacture in flat panels, low cross polarization and the possibility of an electronic control of the beam. This paper reviews different contributions in reflectarrays from fixed-beam to reconfigurable-beam implementations in single and multilayer configurations, including applications for linear and circular polarization, single and multiple beams, pencil and shaped beams, considering single and dual reflectarray configurations.**

***Index Terms*—reflectarray, reflectarray cells, reconfigurable reflectarrays.**

I. INTRODUCTION

The *IEEE Standard for Definitions on Terms for Antennas* [1], designates a reflectarray as: *"An antenna consisting of a feed and an array of reflecting elements arranged on a surface and adjusted so that the reflected waves from the individual elements combine to produce a prescribed secondary radiation pattern"*. According to the standard, other accepted synonyms for this kind of antenna are *"reflective array antenna"* and *"reactive reflector antenna"*.

Because of their advantages if compared to phased-arrays and parabolic reflectors, reflectarray antennas have attracted great attention in the last years [2]. Fig. 1 shows the general architecture of a printed reflectarray working in transmission mode. In that case, a pyramidal horn is used as a feed, but other kind of radiators can also be used. As the reflectarray surface is regularly located in the far field of the feed, a good approach is considering the locally impinging wave as a plane wave with a certain angle of incidence. By introducing a progressive phase-shift in the field reflected by the elements of the array, a pencil beam pointing towards a specific direction can be produced. Alternatively, a prescribed shaped or contoured beam can be generated if a phase-only synthesis technique is properly implemented for obtaining the phase distribution on the reflectarray surface. It is worth to mention that in a reflectarray, the amplitude at each element is imposed by the radiation pattern of the primary feed, therefore only the phase can be controlled at the printed elements. In both pencil- and shaped- or contoured-beams, the local phase is obtained by adjusting one or more geometrical parameters at each element.



(a)

(b)

Fig. 1. Reflectarray antenna. (a) General architecture. (b) Phase and amplitude of the reflection coefficient at one unitary element.

Ideally, a full 360º phase range should be produced by the chosen phasing element, however only few elements can provide the whole phase range. Once the phase distribution on the reflectarray surface is computed according to the beam requirements, the antenna design consists of optimizing each element to provide the required phase value, taking into account the associated losses (see Fig. 1(b)). It is important to mention that most of reflectarray elements are sensitive to the angle of incidence of the impinging wave, producing different phases (and associated loss) for different angles of incidence. An accurate design process should take into consideration the different angles of incidence at each reflectarray cell. The amplitude of reflection coefficient must be nearly equal to one, provided that there is no grating lobe or surface wave generation, because of the ground plane.

However, a reduction in amplitude is produced by the dissipative losses in the dielectric layers and on the conductors.

There are different criteria for classifying reflectarray antennas, according to the number of layers, the number of reflecting surfaces, the polarization, the kind of beam to be radiated, or the possibility of dynamically reconfigure the beam. Under these late criteria, reflectarray antennas can be classified in two main sub-groups: fixed-beam (or passive) and reconfigurable reflectarrays. In a fixed-beam reflectarray, the beam forming is implemented by properly adjusting the dimensions at each element, and cannot be modified. On the other hand, the beam can be dynamically reconfigured or scanned by introducing controllable mechanisms at the element level, in order to change the phase-shift and to reconfigure the beam. Note that reconfigurable reflectarrays will only be "active", when active devices or amplifiers are included in the reflectarray cells, as in the case of the works reported in [3], [4] and [5]. Both types of reflectarrays are considered in this review paper, although a very detailed review of reconfigurable reflectarrays can be found in [6].

II. Basic Concepts On Reflectarray Antennas

The reflectarray concept was firstly introduced in 1963 [7]. That work proposed a surface whose impedance was synthesized to produce a variety of radiation patterns. The experimental demonstration was carried out using a waveguide array which was illuminated by an offset feed, as shown in Fig. 2. The array was composed by 104 square waveguides with a separation between them of 0.6λ. Each waveguide was ended by a short-circuit and the required phase for the reflected wave was obtained by adjusting the length of each waveguide. Unfortunately, the heavy weight and bulky structure made this configuration unattractive for practical applications.

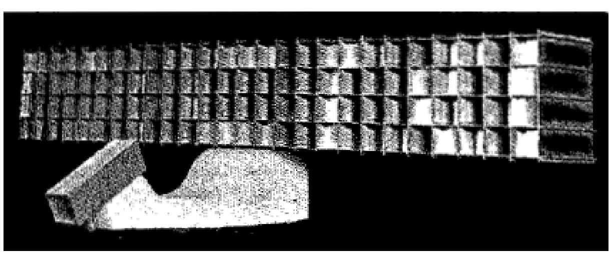


Fig. 2. Experimental demonstration of a waveguide reflectarray. (© 1963 IEEE. Reprinted, with permission, from [7]).

The operating principle of a reflectarray antenna (see Fig. 1) can be explained by considering the reflectarray in transmitting mode with a feed–horn located in a centered or offset position, and assuming that the reflectarray elements are in the far field region of the horn. In this case, the electromagnetic field incident on each reflectarray element at a certain angle can be locally considered as a plane wave with a phase proportional to the distance from the phase center of the feed–horn to each element. From array theory, the phase required at each element i of an array to focus a beam in the direction (θ_b, φ_b) can be written as:

$$\varphi(x_i, y_i) = -K_0 sin\theta_b \cos\phi_b x_i - K_0 sin\theta_b sin\phi_b y_i, \quad (1)$$

where K_0 is the propagation constant in vacuum, and (x_i, y_i) the coordinates of element i. Reflectarray antennas are spatially fed, which means that the phase introduced by the different paths from the feed phase-center and each element must be locally compensated. The phase–shift to be introduced on each reflectarray cell is obtained as the difference between (1) and the phase of the incident field coming from the feed,

$$\varphi_{Ri} = K_0(d_i - (x_i \cos\phi_b + y_i sin\phi_b) sin\theta_b), \quad (2)$$

where d_i is the distance from the phase center of the feed to the cell. For the reflectarray design, the phase–shift must be adjusted in each element to match these phases. A shaped beam can also be achieved if the phase distribution given by Eq. (2) is substituted by an appropriate phase distribution obtained by a phase–only synthesis method, as will be discussed in a later section.

III. Elementary Cells in Reflectarrays

The phase-shift which is required at each element location for producing the predefined beam can be obtained by using different kind of elements. One method is using identical microstrip patches with variable length delay lines attached [8], [9] so that they can compensate for the phase delays over the different paths from the illuminating feed. This kind of element produces a phase-shift in reflection which is proportional to twice the length of the delay line. While this element was firstly proposed for fixed-beam reflectarrays, it has been also used in reconfigurable antennas. In [10], a single-bit phase shifter using a PIN diode operating in the 60 GHz band was used in a 160 x 160 elements demonstrator. The proposed reflectarray cell, shown in Fig. 3, offers a simplified structure for both the reflecting element and the control circuit. The design of a passive single-layer circularly polarized reflectarray which uses a circular microstrip patch attached to four variable length phase delay lines was presented in [11], in the frequency range from 9.6 GHz to 11.2 GHz.

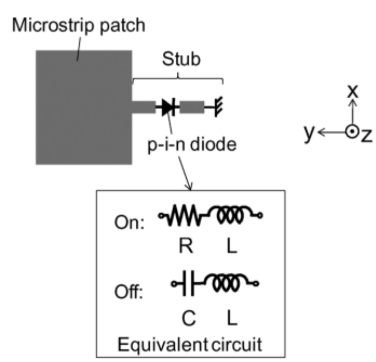


Fig. 3. Basic model of a 1-bit phase-shifter consisted of a microstrip patch with an attached delay line. (© 2011 IEEE. Reprinted, with permission, from [10])

The phase adjustment by the variation of the resonant length of rectangular printed patches [12], [13] is very easy to implement by using printed circuit technology. This phasing technique eliminates some of the inconveniences associated with the stubs. The problem of accommodation of the stubs with lengths of up to half-a-wavelength is eliminated. Additionally, the deterioration of some electrical performances, such a dissipative losses and cross-polarization produced by the bent stubs are reduced. The operating principle of the reflectarrays of variable-sized printed elements is based on the fact that the phase of the reflected waves varies with the resonant length of the elements. A microstrip patch is a resonant antenna, so that its length should be approximately half a wavelength in the dielectric [2]. If the patch length is modified in an array of rectangular patches printed on a grounded dielectric, the phase of the reflected field will be changed. For a resonating patch, a small change in its size produces a wide range in phase variation of the reflected wave [12]. An accurate design of a reflectarray antenna requires taking into account the mutual coupling between the patches of the array, as well as the impact of the impinging wave at each element, which can be locally considered as a plane wave with an associated angle of incidence [2]. The total range of phase variation that can be achieved by varying the length of the patches depends on the electrical thickness of the substrate. For thickness smaller than one tenth of the wavelength, a 330º range can be achieved, which is potentially enough for implementing practical designs, but this range diminishes for thicker substrates. This is the reason for using thin dielectric substrates. However, the phase variation versus the length of the patches is strongly nonlinear and therefore it is very sensitive to frequency variations, reducing the working band of the reflectarray. A significant effort has been carried out in last years to overcome the main limitation of reflectarrays, the bandwidth. Those techniques will be described in the "Broadband Techniques in Reflectarrays" section, but here it is important to mention the stacking of two or more array layers as a simple-to-implement solution.

An array of rectangular metallic patches behaves as a resonant circuit, in which the phase of the reflected field varies with the size of the patches within a range of 180º. When the array is backed by a ground plane, the maximum phase shift range approaches 360º, provided that the separation between the patches and the ground plane is very small compared with the wavelength. When two or more array layers are used, as in Fig. 4, each of them behaves like a resonant circuit, and the phase of the reflected field varies with the patch size in a similar way to that of one layer, but the phase shift can reach values of several times 360º. Therefore, with several array layers, optimized thickness of the substrates and a slight difference between the size of patches in each layer, a smoother and more linear behavior of the phase as a function of the patch size can be achieved, maintaining a phase range greater than 360º. The phase-shifter based on rectangular patches can be used for dual linear or circular polarization. To consider any kind of polarization, the field at each element is broken down into two components parallel to the patch sides, and the phase of each field component is controlled by adjusting the corresponding dimensions of the stacked rectangular patches.

A similar mechanism for adjusting the phase in fixed-beam reflectarrays is to use other geometries of variable-size elements, such as variable-length dipoles [14]–[16], variable ratio rings [17], variable-length slots [18], etc. In this way, the elements can have different scattering impedances and provide the require phase compensation for each feed-cell delay. For circular polarization, another technique consists in having identical circularly polarized elements with variable angular rotation [19].

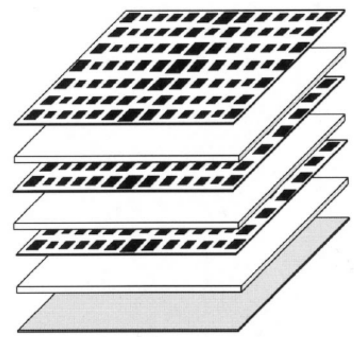


Fig. 4. Multilayer reflectarray made of varying size patches. (© 2003 IEEE. Reprinted, with permission, from [56])

The use of multi cross loop elements of variable loop length for broadband operation in single-layer reflectarrays was proposed in [20]. This topology was modified and used in a dual-band, linearly polarized FSS-backed reflectarray antenna that operates in X and Ka bands [21]. The modified Malta cross was introduced in [22] for increasing the bandwidth of the reflectarray element. The element uses a single-layer configuration and by properly adjusting two parameters of the geometry, the gain bandwidth is improved. The use of fractal-shaped patches for the design of reduced-size reflectarray element is proposed and demonstrated with measures in [23]. The miniaturization capabilities of fractal geometry are exploited at X-band. With this kind of element the reflectarray element can be reduced to $0.3\lambda \times 0.3\lambda$ with a phase range greater than 360º.

Recently, the so called Phoenix cell was proposed in [24] for implementing reflectarrays using a single-layer. The initial geometry is built from a square ring slot as seen in Fig. 5. A metallic ring is inserted into the slot, splitting it in two smaller slots: an inner slot and an outer slot. The phase of the reflected wave is defined by the position of the metallic ring in the initial ring slot. By increasing the side of the metallic ring, the element comes back to its initial geometry. It provides a nearly 360º phase range with low dispersion.

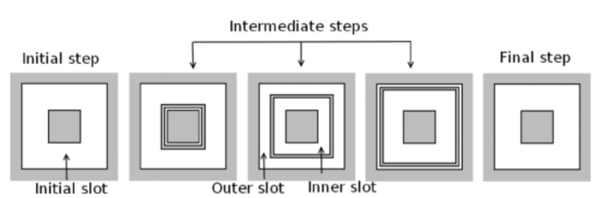


Fig. 5. Phoenix cell complete cycle. (© 2011 IEEE. Reprinted, with permission, from [24])

The so called spiraphase array was originally proposed to offer reconfigurability [25]. This array was based on multi-arm half-wave dipole elements commutated electronically. The electronic commutation of the dipole arms is equivalent to the element rotation on an angle γ resulting in an additional phase shift of 2γ in the reflected circularly-polarized wave (CPW). The fabricated C-band spiraphase reflectarray based on multi-arm dipoles demonstrated acceptable scanning characteristics in the angular sector of $\pm$45. Later, spiraphase-type elements based on shorted ring slots and reactively-loaded ring slots (see Fig. 6) were proposed and investigated in [26] and [27], respectively. These elements demonstrated better bandwidth as compared to the classic dipole/spiral spiraphase-type elements as well as better suitability for wide-angle scanning [28].

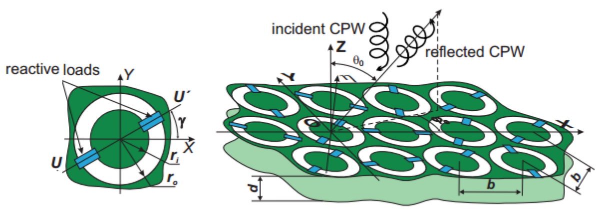


Fig. 6. Sphiraphase-type reflectarray element based on ring slot resonators with reactive loads. (© 2015 IEEE. Reprinted, with permission, from [28])

A technique for synthesizing reflectarray antennas using fragmented elements in a manner that allows the elements of the array to be shaped-optimized so that a high degree of geometrical similarity is maintained between adjacent elements was proposed and demonstrated in [29] and [30]. The idea is that each element in the reflectarray will see an electromagnetic environment that more closely emulates the infinite periodic approach, which is regularly used to compute the reflection properties. This fragmented elements technique can be simultaneously patterned with a visual image while closely maintaining the required reflection phase, as can be shown in Fig. 7.

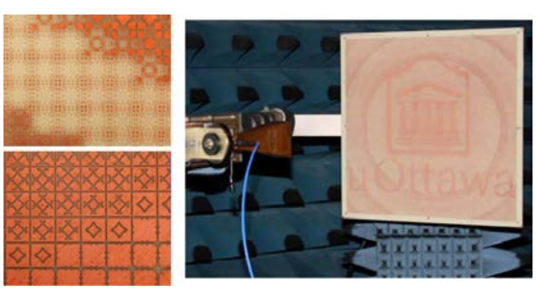


Fig. 7. Similarity shaped reflectarray. (© 2014 IEEE. Reprinted, with permission, from [30])

Despite their multilayer configuration, patches aperture-coupled to delay lines have many advantages over other configurations as the capability to compensate the effects of differential spatial phase delay [31], low losses, low cross-polarization levels and a very linear phase response [32], [33]. The proposed element is shown in Fig. 8(a) and consists of a fixed-sized rectangular patch printed on a dielectric slab, a fixed-sized rectangular slot in a ground plane and a variable length delay line separated by a substrate on the other side. From the slot center, the delay line can be seen as two segments: a matching stub and a variable length delay line. The former is used to adjust the reactance in the input impedance seen from the microstrip delay line, as if it was matched instead of open-ended. The phase of the reflected wave is adjusted by varying the length of the delay line. In the ideal case, the phase in reflection is proportional to twice the length of the delay line. A ground plane eliminates the leakage of energy to the back of the antenna. Although this configuration has been mainly used for single linear polarization, as the case demonstrated in [34] for a shaped-beam, it can be extended to dual linear polarization [35].

For the case of electronically reconfigurable elements, this topology allows a complete isolation between the radiating section and the control devices, including the biasing circuits. Different solutions of aperture-coupled elements for reconfigurable reflectarray antennas have been demonstrated in the literature by using varactor diodes [36], [37], PIN diodes [38] and MEMS devices [39], [40]. Additionally, the delay lines used to tune the phase of the reflected field can be shared by gathering the elements by pairs, producing a phase control at sub-array level, as demonstrated in [38], [40] and [41]. This feature allows reducing the manufacturing complexity and the antenna cost where thousands of elements are required. This kind of gathered element is shown in Fig. 8(b) for the case of a PIN diode which connects two segments of the shared delay line.

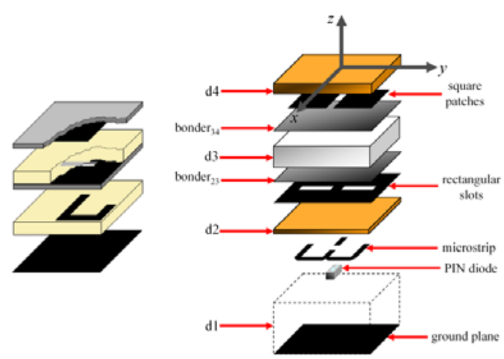
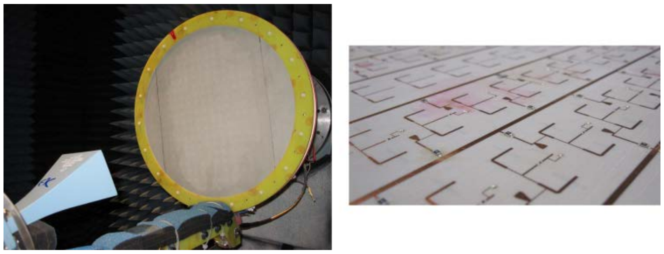


Fig. 8. Reflectarray elements based in aperture-coupled patches. (a) Fixed-beam single element. (b) Reconfigurable-beam gathered element based in PIN diodes.

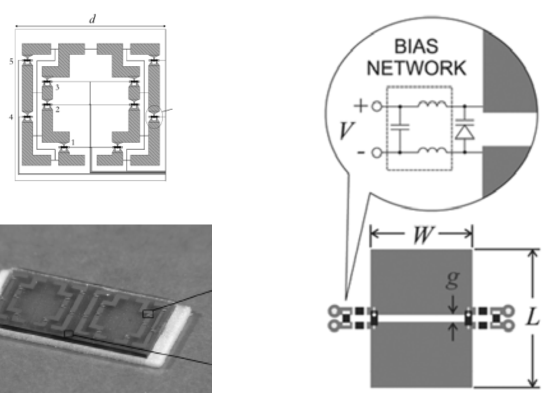
An X-band switching-beam reflectarray antenna using gathered elements which are based on patches aperture-coupled to delay lines was demonstrated in [38]. The phase of each element was controlled by the implementation of surface-mounted PIN diodes. A prototype with 244 radiating elements grouped in 122 sub-arrays was designed and measured in the anechoic chamber. The radiation pattern can be switched between –5º, 0º and +5º, in a plane which is tilted 18.3º below the horizon. The gathering allows reducing the number of PIN diodes to 104 and only 52 are direct biasing simultaneously because of the symmetry of the pointing direction. Fig. 9 shows the manufactured breadboard and the phase control layer, which includes the biasing circuit.



(a) (b)

Fig. 9. Switched-beam reflectarray antenna based in aperture-coupled gathered elements. (a) Manufactured breadboard. (b) Control layer. (© 2012 IEEE. Reprinted, with permission, from [38])

The previous reconfigurable reflectarray, as in other reported works [10][36][37][39], are based on the concept of a fix printed resonant patch coupled (or attached [10]) to a switched or reactively loaded delay line. As an alternative to this concept, several reconfigurable reflectarray cells based on the concept of tunable resonator have been proposed [42], [43], [44]. In this case, switches or varactors are integrated in the resonant reflectarray element in order to electronically control the phase of the reflected field, see Fig. 10. On one hand, these reconfigurable reflectarray cells offer more simplicity, since they are manufactured in a single layer, and lower losses due to the elimination of delay lines. On the other hand, the controllable devices (MEMS, PIN or varactor diodes) are integrated on the radiating element, requiring accurate and efficient electromagnetic models for the analysis of the reconfigurable cells and for the design of the antenna [45]. In addition, the complexity of the biasing lines in a single layer can be considerable. Using tunable reflectarray cells made of two halves of a microstrip patch connected by two varactor diodes, a complete reflectarray reflectarray capable of reconfiguring the beam in real time was satisfactorily demonstrated in [42]. Although many of this type of reconfigurable reflectarray cells have been used in single linear polarization, reconfigurable elements for dual polarization have also been successfully demonstrated [46].



(a) (b)

Fig. 10. Reconfigurable reflectarray cells based on tunable resonator. (a) Top view and manufactured cells from [44] (© 2008 IEEE). (b) Scheme of the cell with two varactor diodes from [42] (© 2005 IEEE).

In addition to printed arrays in single- or multi-layer configurations, where the different layers of the antenna are photo-etched and bonded to form a stacked structure (in the case of multi-layer), the phase-shift at the element level can also be adjusted by using other techniques. A single-layer reflectarray made of perforated dielectric substrate is demonstrated in [47]. The antenna is fabricated by drilling air holes with different diameters on a dielectric substrate. In this way, the effective permittivity of the substrate is locally changed. Fig. 11 shows a schematic of the proposed solution, including a manufactured reflectarray composed of 841 elements, working in Ka band.

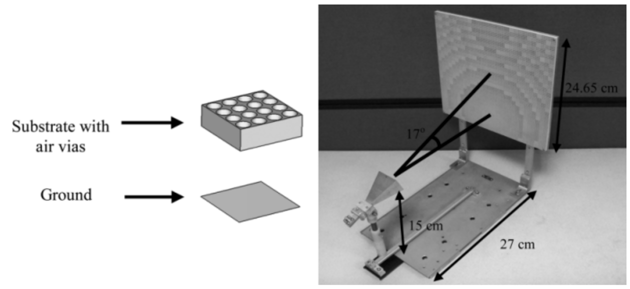


Fig. 11 Ka-band reflectarray antenna made of perforated dielectric substrate. (© 2012 IEEE. Reprinted, with permission, from [47])

Metal-only reflectarray has been proposed in millimeter wave bands, where the losses of dielectric materials can impact on the antenna performance [48], [49]. Fig. 12 shows a reflectarray antenna based on metallic-rectangular-grooves. The manufactured breadboard with 30 cm diameter and almost 6000 rectangular grooves on its metal surface provides a gain of 42.3 dB at 75 GHz.

Fig. 12 Metal-only reflectarray antenna made of rectangular grooves for operating at 75GHz. (© 2011 IEEE. Reprinted, with permission, from [49]).

Quasi-dipole unit cells were proposed and demonstrated in [50]. The substrate of the quasi-dipole is oriented perpendicular to the array surface, as shown in Fig. 13. Two breadboards were manufactured and tested, each one with 8 x 8 elements. The first demonstrator points towards broadside while the second one points towards 20º.

The proper choise of a reflectarray element depends on different aspects of the design and requirements. Bandwidth requirements, profile, polarization constraints, losses, cross-polarization levels, phase-control requirements and cost, are some of the features which should be taken into account. In addition to a specific analysis for each kind of element, there are different figures of merit which can be helpful when choosing the final topology [51], [52], [53].

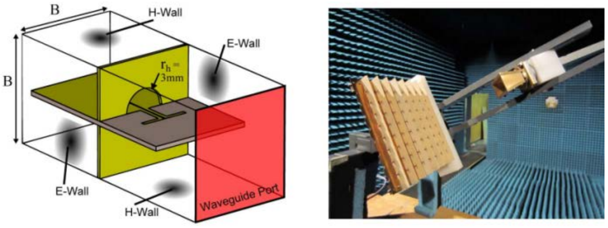


Fig. 13. Quasi-dipole reflectarray antenna (a) Unit element. (b) Demonstrator. (© 2014 IEEE. Reprinted, with permission, from [50])

IV. Broadband Techniques in Reflectarrays

Significant effort has been spent for overcoming one of the most important drawbacks of reflectarray antennas: narrow bandwidth. There are different techniques for substantially increasing the bandwidth of this kind of antenna.

The bandwidth limitation produced by the radiating element is the most significant for moderate size reflectarrays, as demonstrated in [54]. A reflectarray based on artificial impedance surfaces has been proposed in [55] to increase the bandwidth of reflectarrays using a single layer of printed elements arranged in a regular lattice with period of less than half-a-wavelength. This configuration, based on the reduction of the period, allowed increasing the bandwidth up to a 20% for a reflectarray of around 10 wavelengths in diameter. For this antenna diameter, the errors introduced by the differential spatial phase delay do not produce a significant reduction in the bandwidth.

When the phase–adjustment is implemented by varying the resonant dimensions of the printed patches, several schemes have been proposed to improve the element bandwidth, consisting of stacking several patches [13],[56],[57], varying the geometry of the conductive patch [51], [58], or using multi–resonant elements in a single layer for passive [59],[60],[61] and reconfigurable cells [62]. Stacked metallic rectangular patches [13],[56] or rings [57], have been proposed as broadband reflectarray elements where the resonant frequencies are adjusted to improve the linearity of the phase curves. In a similar manner, reflectarray elements based on several resonant dipoles or crossed–loops on the same dielectric layer have been proposed [59],[60],[61], where the relative lengths of the parallel dipoles [59],[60], or concentric rings [57], [61] are adjusted to improve the bandwidth of the reflectarray element. For reflectarray elements based on two layers of varying–sized patches, already mentioned in section III, a 40–cm reflectarray was designed, built and measured [13], showing a 16.7% bandwidth (11–13 GHz) for 30dBi gain. Table I summarizes the main features of few of the previously mentioned elements.

On the other hand, the bandwidth limitation produced by the differential spatial phase delay, is critical for electrically large antennas and small F/D ratios [63]. Usually, the required phase value to compensate for the different paths of the wave from the feed horn to each array element is only achieved at the central frequency within a range of 360º. When frequency varies, a phase error proportional to the differences in path length is produced. This effect produces a small reduction in gain for pencil beam reflectarrays and produces a significant distortion of the beam shaping in contoured beam reflectarrays when frequency varies out of the central frequency [64].

Table I Main features for some reflectarray elements with phase adjustment varying the resonant dimensions (NML: Number of Metallic Layers, BW: Bandwidth, * Including varactors)

Ref.	Type of element	NML/ Size [λ]	Freq. [GHz]	Phase range [deg.]	Element BW	Reflectarray BW
[13]	Stacked patches /	2 / 0.56	12.0	>400 / NA	NA	16.7% (1.5dB drop)
[56]	Stacked patches /	3 / 0.56	12.0	> 650 / NA	NA	10% (0.5dB drop)
[57]	Double Circular Rings	1 / 0.32	9.8	<330 / < 0.50	>20%	NA
[58]	Patch Loaded With Slot	1 / 0.70	12.5	~360 / NA	4%	4%
[59]	Coupled Structures	1 / 0.55	35.0	673 / NA	NA	4.8% (3dB drop)
[60]	3 Parallel Dipoles	1 / 0.50	300.0	>400 / <0.25	20%	13%
[61]	Double Cross Rings	1 / 0.44	22.0	>500 / NA	NA	10% (1dB drop)
[62]	Reconfig.Double Square Rings	1 / 0.54	5.4	~380 / <3.5*	2.4%	NA

Several broadband techniques have been proposed to reduce the effect of the differential spatial phase delay. The first one consists of compensating the spatial phase delay in a given frequency band with the phase–shift produced by three layers of varying–sized patches [56]. A second technique is to implement delay lines in order to compensate on each reflectarray element the real phase delay in the whole range (several times 360º) by using stubs with a length that varies in a range of several wavelengths [31]. A third technique consists of a multi–facet configuration, which approaches a parabolic surface using flat panels [65].

A technique was proposed in [56] to design a reflectarray in a frequency band defined by the extreme frequencies f_1 and f_2, by optimizing the dimensions of three stacked patches for the two linear polarizations, using a Fletcher Powell algorithm, to match simultaneously in each element (*i*) the phase–shift at the central frequency ϕ_{oi} (limited to a 360º) and the phase delay difference, defined as $D_{di}(f_1,f_2) = \phi_{di}(f_1) – \phi_{di}(f_2)$, being $\phi_{di}(f)$ the required phase delay (not limited to a 360º range) at frequency f. It was demonstrated that three stacked patches are required to provide sufficient degrees of freedom in order to match the required phase at several frequencies. Following this optimization process, a 10 % bandwidth was achieved for a 1–m reflectarray at 12 GHz by compensating the phase delay in a range of 5 times 360º [56]. For a bandwidth larger than 10%, the phase delay must be compensated at several frequencies in the band, as shown in [66], [67].The improvement of bandwidth using true-time delay (TTD) phase compensation in reflectarrays was demonstrated in [31]. For this purpose, two pencil-beam reflectarrays have been designed at 9.65 GHz using two different phase distributions implemented by patches aperture-coupled to delay lines, as those shown in Fig. 8(a).

The first distribution was limited to one cycle of 360º and the second distribution was expanded up to 3 times 360º. A bandwidth improvement is demonstrated in the second case, as a result of the TTD.

Fig. 14 shows the antenna gain as a function of frequency for the two designed reflectarrays, based on truncated and unlimited phase distributions. The gain curves corresponding to two theoretical phase distributions have been included, as references. The first ideal curve represents the gain in the 8.5 GHz – 11.90 GHz band obtained from an ideal truncated phase distribution at 9.65 GHz. This case is equivalent to the design of a reflectarray with 360º phase truncation, using ideal reflectarray elements that produce the same phase-shift at every frequency. In this case, the phase distribution on the reflectarray remains fixed when frequency varies; however, the required phase to produce a focused beam should vary with frequency proportionally to the true-time delay, as in the case of parabolic reflectors. The second ideal curve represents the gain at each frequency corresponding to the ideal phase distribution, compensated using TTD. Therefore, both ideal curves coincide at the central frequency and their difference represents the diminution of gain produced by the effect of differential phase delay in reflectarrays. Note that the behavior of the gain for the reflectarray with truncated phases is similar as the one of the ideal phase at 9.65 GHz, being the reduction in gain for the reflectarray mainly produced by the losses in the dielectric materials (0.5 dB) and by some distortion of the element phasing at extreme frequencies. On the other hand, the gain curve of the TTD reflectarray should be similar as the one obtained for the ideal compensated phase distribution, which is true from 9.2 GHz to 10.8 GHz. In this frequency range, the TTD curve is similar to the ideal case with a reduction in gain less than 1 dB, as a result of ohmic losses and small phase errors out of central frequency. For extreme frequencies, the gain drops because the phasing produced by the elements are much different that the ideal case. These curves show clearly that the introduction of TTD lines significantly increases the bandwidth of the reflectarray. For example, the bandwidth for a 0.3 dB gain variation is 10.1% for the reflectarray with truncated phase and 20.0% for the TTD reflectarray. If the gain variation is limited to 1.5 dB below the maximum, the bandwidth increases from 17.8% to 26.7% for the TTD reflectarray.

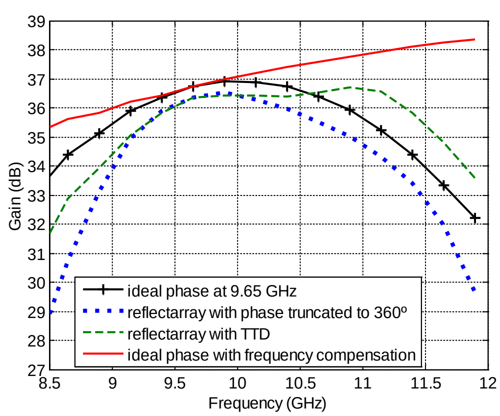


Fig. 14. Gain comparison for the two designed reflectarrays and the gain using ideal phases. ((© 2008 IEEE. Reprinted, with permission, from [31])

Fig. 15 shows the relative bandwidth in percentage for a variation in gain of 0.3 dB, as a function of the reflectarray electrical size for both cases: when the phase distribution is limited to 360º and TTD. The bandwidth of a reflectarray with phase distribution limited to 360º behaves in a similar way to that of a zoned lens antenna. As can be seen, the errors produced by the non-constant path from the feed horn to each element of the reflectarray are more important in large reflectarrays and can be compensated through the introduction of TTD lines. In conventional reflectarrays, the bandwidth decreases as the electrical size of the antenna increases. On the other hand, the relative bandwidth in the case of TTD converges asymptotically for large reflectarrays, because bandwidth is only limited by the reflectarray element and not by its size. These results show that a 20% bandwidth can be achieved for reflectarrays with aperture dimensions larger than 25 wavelengths.

Previous techniques can be used to compensate the phase delay for certain antenna dimensions, defined by a limited number of 360º cycles. The limit for the delay lines is imposed by the room available for the stub length, while the limit in three–layer reflectarrays is given by the capability of compensating the phase delay by optimizing the three–stacked patches. The last one can be compensated in a 10% bandwidth for reflectarray apertures up to 70 wavelengths, assuming an F/D=1.

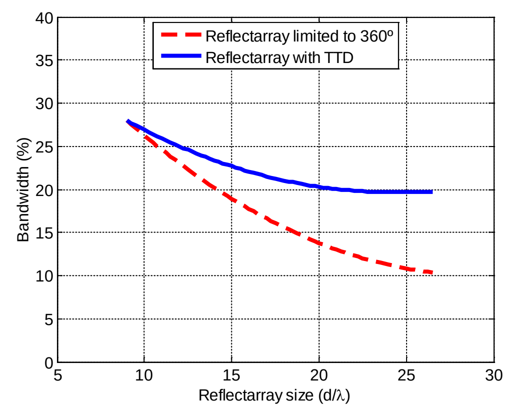


Fig. 15. Bandwidth comparison, at 0.3 dB, between a phase-shift limited to 360º and TTD for different reflectarray sizes. (© 2008 IEEE. Reprinted, with permission, from [31])

A solution to improve the antenna bandwidth in large apertures consist of a facetted configuration that approximates the shape of a parabolic surface using flat reflectarray panels, so that the number of 360º cycles is limited in each flat facet [65]. The multi–facet configuration is also compatible with the previous techniques for compensating the phase delay in a limited bandwidth, so the number of panels can be reduced in order to simplify the manufacture or deployment of the antenna. A recent development using the 1–D multi-panel architecture (Fig. 16) is the NASA/JPL's Wide Swath Ocean Altimeter (WSOA) in Ku–band [68]. The aperture (2m x 0.5m) is made of five reflectarray panels, which make up a piecewise planar approximation of a parabolic cylinder a with a 1.125–m focal length.

Fig. 16. Photo of the piece-wise flat reflectarray for WSOA in Ku-band (Courtesy of JPL, from [2] © 2008 John Wiley, Fig. 7.58)

The concept of miniaturized-element frequency selective surfaces (MEFSSs) has recently been proposed and demonstrated within the frequency range of 8 GHz to 12 GHz. Using this concept, a 40% bandwidth with no significant chromatic aberrations was shown in [69]. This kind of element allows to obtain a TTD response, but overcoming the intrinsic narrowband limitation present in resonant elements. MEFSSs are composed of periodic structures formed by miniaturized, nonresonant elements. Each element is a lowpass type MEFSS composed of a stack of nonresonant patches separated from one another by thin dielectric substrates and backed by a ground plane. Because of the subwavelength nature of the elements, they are also less sensitive to the angle of incidence. A slightly simpler approach using filters theory consists in designing the reflectarray antenna from the point of view of an impedance surface, instead of array theory [70].

Transformation optics technique has been recently proposed for improving the bandwidth in the design of reflectarray antennas [71]. While the phasing of the incident field has been traditionally accomplished by using phase shifting elements placed on the surface of the array, in the proposed example the phasing of the incident field is realized using the effective material formed by an array of sub-wavelength dipoles placed in front of a planar reflector. The non-resonant nature of the short dipoles increases significantly the relative bandwidth.

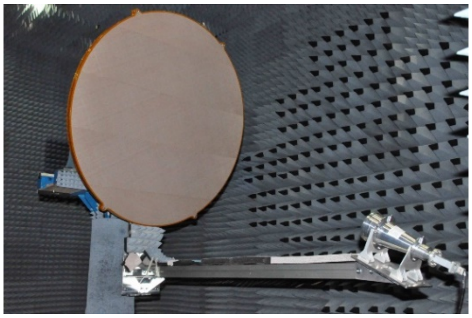
V. Shaped, Contoured and Multi-Beam Reflectarrays

Shaped and contoured beams can be easily generated using reflectarrays by implementing an appropriate phase–shift on the reflectarray elements. A shaped–beam reflectarray was reported for first time in 1993 to provide a cosecant squared pattern [72]. Later a reflectarray demonstrator was reported for DBS applications [73]. In that case, the reflectarray was designed using a shaped reflector previously manufactured for a DBS European coverage in Ku–band. The required phase–shift at 14 GHz was obtained on each reflectarray element from the distance between the shaped surface and the flat surface where the reflectarray was placed. A significant improvement in the design technique was the implementation of pattern synthesis to obtain directly the phase distribution on the reflectarray without the previous design of a shaped–reflector [74]. The pattern synthesis applied to shaped–beam reflectarrays provides some advantages with respect to surface shaping in conventional reflectors. First of all, the phase synthesis is not constrained by geometrical parameters and therefore is more flexible for synthesizing any required radiation pattern. In contoured beam reflectarrays, the phase can be synthesized independently for each polarization, even to generate a different pattern for each polarization as demonstrated in [75]. Also, the real incident field on each reflectarray element for each polarization can be taken into account in the pattern synthesis, which allows to include the near field radiated by the feed–horn [76] or to include separate feeds for each polarization [75]. In addition, the reflectarray can be designed to change the polarization, for example, to convert linear into circular polarization just by adding a 90º phase–shift in one linear polarization with respect to the orthogonal one.

In reflectarrays, the synthesis of radiation patterns is constrained by the feed that imposes the amplitude of the incident field on each reflectarray element. In consequence, a technique known as *phase–only* synthesis must be applied to synthesize the required shaped patterns. Several phase–only techniques have been developed to obtain shaped beams using phased–arrays [77]–[79], The same techniques can be applied to reflectarrays, but the problem is more challenging because of the very high number of elements in reflectarrays. The *Intersection Approach* technique, which was previously developed for phased–arrays [77], has been successfully applied to the design of reflectarray antennas for contoured–beam DBS antennas, [64], [66], [67], [74], [75], [80] and SAR interferometry [81].

Contoured beam reflectarrays made of three layers of varying–sized patches have been successfully designed for Direct Broadcast Satellite (DBS) applications [75], [67], using the *Intersection Approach* and the broadband optimization technique described in section IV. A 1.2–meter reflectarray demonstrator has been designed to accomplish the requirements of a DBS mission in Tx (11.7–12.2 GHz) and Rx (13.75–14.25 GHz) frequency bands that provides “South Pan–American coverage (PAN–S)” in dual-linear polarization from the Amazonas satellite [67]. The reflectarray demonstrator and the measured contoured patterns for H-polarization at 11.7 GHz are shown in Fig. 17. The results obtained from this demonstrator show that a reflectarray can be designed to fulfill the typical requirements of Tx–Rx DBS antennas.

For multi–beam applications requiring several simultaneous beams, a reflectarray can be used to generate a beam associated to each feed, in a similar manner as in multi–fed reflectors. However, the flexibility provided by reflectarrays to achieve any value of phase–shift independently for each linear polarization, can be used to generate different beams in each polarization, to improve the antenna performance, or to produce various simultaneous shaped beams.



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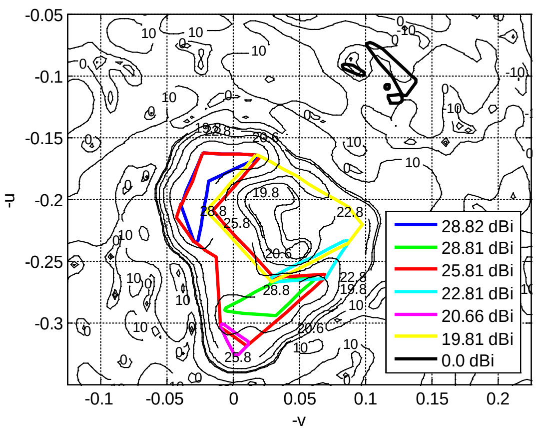
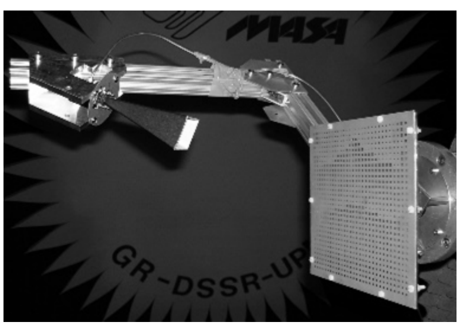


(b)

Fig. 17. Tx-Rx reflectarray antenna for South American coverage. (a) Manufactured demonstrator. (b) Measured co–polar radiation pattern (H–polarization) at 11.70 GHz. (© 2011 IEEE. Reprinted, with permission, from [67]).



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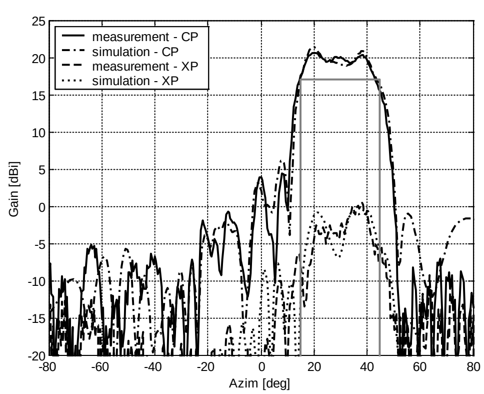

(b)

Fig. 18. Three-beam reflectarray antenna in Ka-band. (a) Antenna demonstrator with the feed for one lateral beam. (b) Simulated and measured azimuth pattern for one lateral beam.

It was demonstrated in [82] that several simultaneous shaped beams can be achieved in a one–feed–per–beam basis for a terrestrial point–to–multipoint application in Ka–band (25.5 GHz). The antenna demonstrator (Fig. 18(a)) was designed to generate three independent shaped beams, covering adjacent 30º sectors in azimuth with the same squared cosecant pattern in elevation. The positions of the lateral feeds were optimized to generate the shaped beams with the appropriate direction and minimum distortion. The measured co–polar and cross–polar radiation patterns shown in [82] agree very well with the simulations in both azimuth and elevation planes, see Fig. 18(b), for azimuth patterns of one lateral beam. These results demonstrate that several shaped beams can be generated using reflectarrays.

VI. Dual–Reflector Configurations

Dual–reflector antennas using a reflectarray as sub, main or both reflectors [83] can be used to reduce the antenna volume, compensate the cross-polarization or to improve other electrical performance. A parabolic reflector with a reflectarray as subreflector has been proposed for compensating the errors on the surface of very–large deployable reflectors [84] and for beam scanning in a limited angular range [85]. This antenna configuration combines the broadband of the parabolic reflector with the simplicity of manufacturing a small sub–reflectarray. In addition, this dual–reflector configuration can be used to scan or reconfigure the beam by electronically controlling the phase–shift at the elements of the sub–reflectarray.

In [86], an offset parabolic reflector antenna which employs a reflectarray subreflector to tilt the focused beam from the boresight direction at 94 GHz was presented and experimentally demonstrated. The subreflector consisted in 784 patch elements in a single layer, which was designed to deflect the beam 5 deg from boresight direction in the azimuth plane. Fig. 19 shows the fabricated demonstrator. To provide an electronic beam scanning at sub-millimeter wave frequencies, a dynamic control of the phase distribution on the reflectarray can be implemented by using a tunable liquid crystal layer between the patches and the ground plane [87].

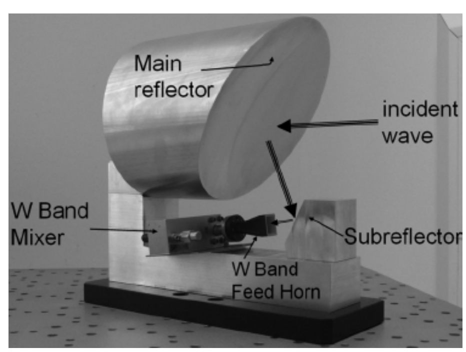

Fig. 19. Reflectarray antenna as a subreflector in a dual reflector system at 94 GHz. (© 2009 IEEE. Reprinted, with permission, from [86])

A dual-reflectarray demonstrator was designed to provide a collimated beam with very low cross-polarization (30dB of cross-polar discrimination) in a broad frequency band, covering transmit and receive frequencies in Ku band for satellite communications (12-15GHZ) [88]. Both reflectarrays were designed using broadband elements based on variable-size patches in a single layer for the main reflectarray and two layers for the sub-reflectarray. A demonstrator with a 50-cm main reflectarray and 40-cm subreflectarray has been manufactured and tested, see Fig. 20. The measured radiation patterns are compliant with the design requirements, see Fig. 20(b).

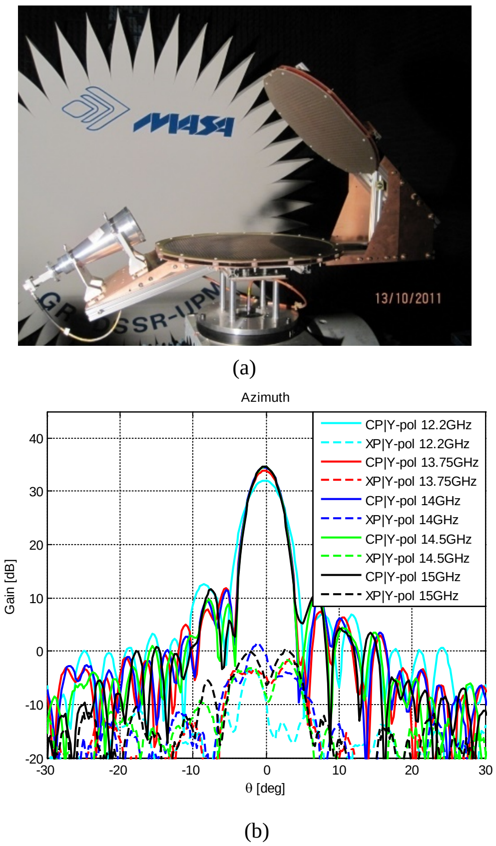

Fig. 20. Dual reflectarray antenna in Ku-band. (a) Antenna demonstrator. (b) Measured azimuth radiation patterns for V polarization (12.2-15.0 GHz). (© 2013 IEEE. Reprinted, with permission, from [88])

The necessity of bidirectional high data rate satellite links in emergency conditions where conventional telecommunication infrastructure is damaged or unavailable, makes reflectarrays an attractive solution for implementing deployable, transportable and easily repointing high gain antennas. In [89] an innovative Ku-band PIN diode-based reconfigurable reflectarray antenna for bidirectional satellite links was proposed. The proposed antenna is a dual-reflectarray made up of three components: a primary feed, a passive rectangular sub-reflectarray and a main reconfigurable reflectarray with 1-bit control. The architecture of these components has been optimized with the aim of achieving the required easy transportation and further deployment. Fig. 21 shows the reflectarray antenna in both transportation and deployed configurations, including the manufactured demonstrator. The antenna was designed to provide a directive beam with electronic scanning capabilities within an angular range of ±5 deg with respect to a nominal direction for both Rx (10.7-12.75 GHz) and Tx (14-14.5 GHz) bands.

Although this antenna has been included here as an example of folded-optics reflectarray, this is also a good example of the easy deployment capabilities offered by this kind of antenna.

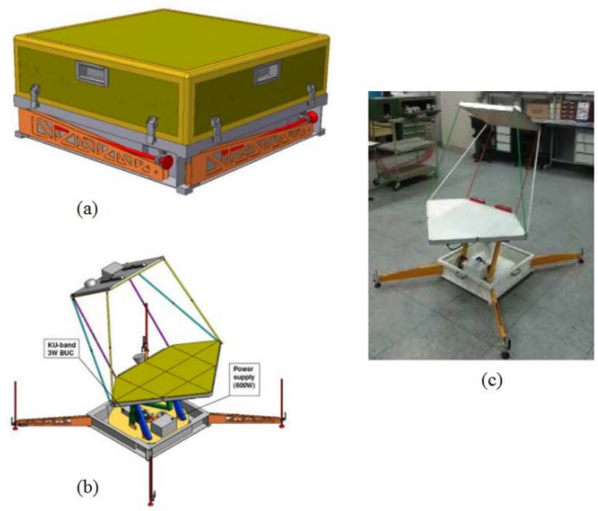

Fig. 21. Transportable reflectarray antenna for satellite Ku-band emergency communications. (a) Transportation configuration (b) Deployed configuration. (c) Manufactured breadboard. (© 2015 IEEE. Reprinted, with permission, from [89])

VII. New Technological Challenges

Reflectarray antennas allow a wide variety of applications in different frequency ranges. They allow the use of emerging technologies in order to improve their electromagnetic characteristics or increase their versatility. Here we mention just a few technological challenges in which reflectarrays are becoming an interesting solution.

A. *Deployable and Inflatable Reflectarrays*

For large apertures, deployable reflectarray antennas made of multiple flat panels [65], can offer some mechanical advantages compared to deployable reflectors in space applications, such as a reduction of the stowage volume and a simplification of the deployment in the space. For example, antennas with multiple panels in only one dimension, as the one in Fig. 16, can profit from the deployment mechanisms used in solar arrays.

The concepts developed for inflatable reflector antennas, based on “rigidizable” membranes and inflatable support structures have been applied in JPL/NASA to develop a new type of inflatable reflectarray antennas [90]–[92]. Several inflatable reflectarrays have been co–developed by JPL and ILC Dover, Inc.; the first one of 1–meter diameter at X–band, and others of 3–meter diameter to operate in Ka-band, see Fig. 22. The Ka-band reflectarrays were composed of conductive patches printed on one side of a 5mil (0.13 mm) polyimide membrane with 5–μm copper cladding on the opposite side to form the ground plane. The membrane was maintained flat by tensioning forces in 16 catenary points. The measured radiation patterns show an antenna gain of

54.4 dBi at 32 GHz, a 0.22° beamwidth, sidelobes 27 dB below to the maximum and cross–polar levels of –40 dB in the main beam.

Fig.22. Inflatable reflectarray. (Courtesy of JPL-NASA)

Because of their easy deployment capabilities, reflectarrays have been recently chosen by NASA as high gain platforms to be used in CubeSat telecommunications [93]. The first mission, named Integrated Solar Array and Reflectarray Antenna (ISARA) uses a K/Ka band reflectarray which is implemented in the opposite face of a solar panel. The second mission which is named MarCO has been proposed to fly alongside the InSight mission to Mars in order to provide telecommunications link to transmit Entry, Descent and Landing (EDL) data to Earth. It will use an X-band deployable reflectarray, as that shown in Fig. 23.

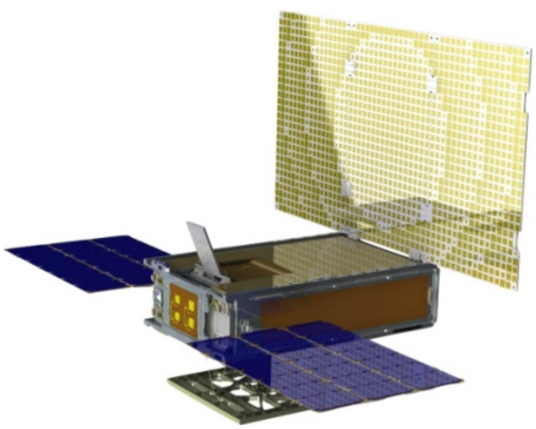

Fig.23. MarCO CubeSat platform, including a deployable reflectarray antenna for high-gain telecommunications link. (Courtesy of JPL-NASA)

B. Reflectarrays and solar cells

With the improvement of solar cells technology, reflectarray antennas have become an interesting solution for combining solar panels and antennas using the same platform. The integration of these two components on a satellite platform significantly reduces the volume, mass and cost of a satellite. The use of reflectarrays combined with solar cells was proposed in [94] for the first time. In [95], the feasibility of integrating reflectarray antennas on a thin-film solar cell, preserving good performance in terms of both solar cell and reflectarray efficiency, was demonstrated at unit cell level. A phase range of 270º was demonstrated in X-band, with an average microwave loss of 0.25 dB and average optical transparency in visible spectrum of 85%. The results show a small blockage of the reflectarray element on the solar cell and consequently, large solar panel efficiency. In that case, copper was used for the reflectarray cell. The optical transparency was improved to 90% by using a transparent conductive oxide (TCO), but increasing the microwave loss to 2.45 dB. Therefore, a trade-off between achieving high solar cell efficiency and good microwave performance must be done.

TCO has also been used for implementing optically transparent reflectarrays at higher frequencies [96]. A sub-wavelength rectangular patch operating at 26 GHz was fabricated using indium tin oxide (ITO) and a 1-mm thick quartz substrate. Although the effect of conductor losses must be reduced, the experimental measurements in waveguide simulator demonstrates promising results. Using this element, a 10 element x 10 element reflectarray was designed to produce a beam at 20deg off-broadside.

A Ka-band reflectarray integrated with solar cells was proposed and experimentally demonstrated in [97]. The antenna shows a 1-dB gain bandwidth of 8.75% with optical blockage of 17.6% on solar energy. Crossed dipoles were used as unitary element, allowing dual linear polarization and moderate blocking area, while the multilayer solar cells were used as the reflectarray substrate.

C. 3-D Printed Reflectarrays

Polymer-jetting 3-D printing technology has been used to fabricate a low-cost dielectric reflectarray antennas operating at 100 GHz [98]. This technology allows rapid prototyping and is a previous step towards the future implementation of reflectarray antennas at terahertz frequencies where the conductor losses are critical. This technique was demonstrated with the manufacturing of 3 different prototypes made of variable height dielectric slabs with low permittivity. One reflectarray was optimized for minimum phase wraps, a second prototype was optimized for minimum element loss, and finally the third reflectarray was sampled to 1-bit in a similar way to a Fresnel zone reflector. Fig. 24 shows the manufactured prototypes, where each unitary cell size is 1.5 x 1.5 mm^2.

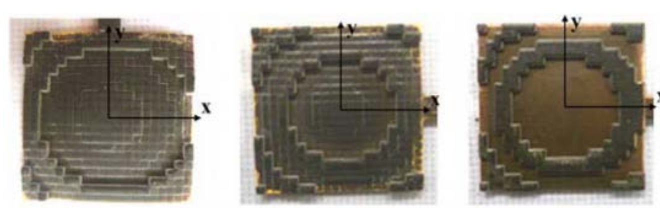

Fig.24. 3-D printed dielectric reflectarray antennas operating in the band of 100 GHz. (© 2014 IEEE. Reprinted, with permission, from [98])

D. Reflectarrays at Terahertz and Optical Frequencies.

Reflectarray antennas are attractive candidates for manipulating electromagnetic radiation in the terahertz band of the spectrum. The realization of reflectarrays operating at 1 THz was proposed and experimentally demonstrated in [99].The proposed antenna uses square metal patches as resonant phase-controlling elements. Particular attention was paid to the choice of suitable materials at such frequencies, while the tolerances of manufacturing techniques were also taken into account. The stacked structure consisted in a gold patch, a polydimethysiloxane (PDMS) substrate, which exhibits relatively low loss in the terahertz range, and a platinum ground plane. The metal layers were characterized through their surface impedance determined by a Drude model. Fig. 25 shows the fabricated prototype with size 50 x 50 mm^2, containing 360 x 360 elements arranged in sub-arrays. A similar reflectarray was proposed, designed and demonstrated in [100] using orthogonal strip dipoles in an interlaced triangular-lattice configuration. This antenna was proposed as a polarization beam splitter for efficiently deflect the incident waves into different directions depending on the incident linear polarization.

For higher frequencies, namely in optical bands, the rapid efficiency degradation in conventional metallic antennas can be compensated by using dielectric resonators. In [101], a dielectric resonator reflectarray was proposed and demonstrated by using cylindrical shape resonators. The material for the resonator was TiO_2 because of its manufacturability and functionality. The substrate was a 390 µm-thick silicon waver coated with a 200 nm thick silver film. The phase variation obtained from the resonance mechanism can nearly cover the full 360º range, while the strongest absorption amounts to only -3dB, which is a promising value at the operating frequency (633nm). Fig. 26 shows the proposed array formed by dielectric resonators.

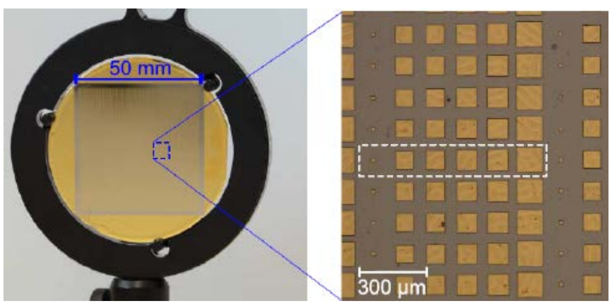

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Fig. 25. Terahertz reflectarray based in resonant metallic patches. (Courtesy of Prof. C. Fumeaux from University of Adelaide. © 2013 OSA. Reprinted, with permission, from [99])

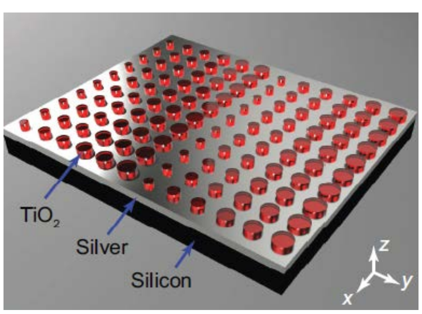
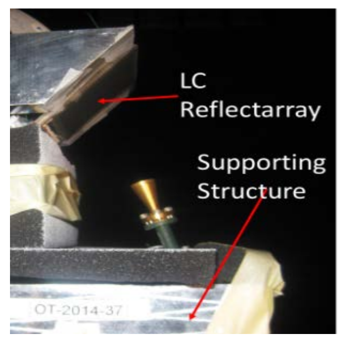


Fig. 26. Dielectric resonator reflectarray for optical frequencies. (Courtesy of Prof. C. Fumeaux from University of Adelaide. © 2013 OSA Reprinted, with permission, from [101])

E. Liquid Crystal Reflectarrays.

For applications in the millimeter and sub-millimeter wave range, electronic beam scanning has been proposed and demonstrated by using reflectarrays based on Liquid Crystals (LC) [102], [87], [103], where the phase of the reflected field is controlled by the bias voltage applied to the liquid crystal. Several demonstrators reported in the literature have shown the capabilities of beam scanning and beam switching with liquid crystal reflectarrays. In reference [104], 1-bit phase quantization was used to produce a switchable radiation pattern shape from sum to difference, whereas a continuous phase variation was used to implement a LC reflectarray with scanning capabilities in one plane at 35 GHz [102] and 77 GHz [103]. A LC-reconfigurable reflectarray at 78 GHz has been proposed in a folded configuration [105] to provide beam scanning in one plane with higher gain (25dBi). This arrangement uses a passive reflectarray to collimate the beam and to twist the electric field.

A LC-reflectarray that provides beam scanning over a wide angular range (55º) in the frequency band 96-104GHz has been reported in [106], see Fig. 27. The large bandwidth has been achieved thanks to the use of a multi-resonant cells made of 3 parallel dipoles [107]. In addition to the broadband behavior of the LC-cell, the proposed biasing technique allows to provide the required voltages for beam scanning at different frequencies within the range 96-104GHz (frequency reconfiguration and beam scanning). The measured radiation patterns (see Fig 26(b)) show that this technology is very appropriate for beam scanning antennas in the sub-millimeter and THz range.



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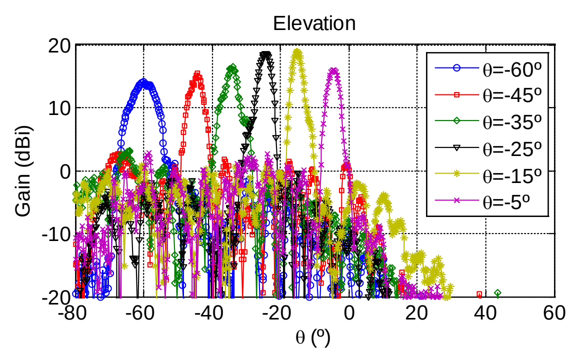
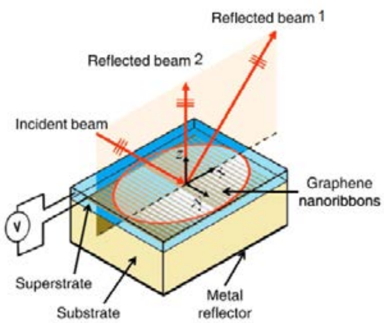


(b)

Fig. 27. LC-reflectarray for beam scanning at 100 GHz. (a) Prototype. (b) Measured elevation radiation patterns at 100 GHz. (© 2015 IEEE. Reprinted, with permission, from [106])

F. Reflectarrays Using Graphene

The use of graphene for reflectarray antennas at THz has been proposed for fixed [108] and reconfigurable beams [109]. Graphene's unique electronic band structure leads to a complex surface conductivity at THz frequencies, which allows the propagation of very slow plasmonic modes, resulting in a drastic reduction of the size of each element of the array and thereby good array performance. On the other hand, the electrical conductivity of graphene can be tuned by electronically doping. By exploiting this feature, reconfigurable-beam reflectarrays can be efficiently implemented from THz to mid-infrared bands [110]. Fig. 28(a) shows a schematic of a gate-controlled reflectarray device based on graphene nanoribbons operating at 27 THz. The bi-dimensional and semi-metallic nature of graphene allows for electrical tunability (not possible with conventional metals) by simply biasing electrostatically the graphene device. By optimizing the widths of the nanoribbons, the incident beam can be switched between the specular and the broadside directions, see Fig. 28(b) using a very simple two-state biasing which allows to connect all the nanoribbons to the same voltage at the same time. A continuous steering of the beam is also possible by implementing a more complex biasing with independent gating for each nanoribbon.



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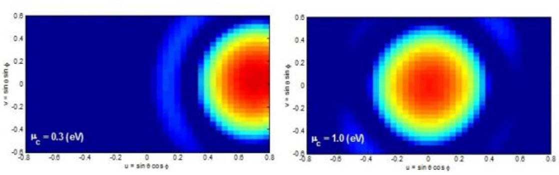

(b)

Fig. 28. Gate-controlled mid-infrared reflectarray formed by an array of graphene nanoribbons. (a) Schematic of the proposed device. (b) Far-field radiation pattern produced by the reflectarray for the two bias condition.

VIII. CONCLUSIONS

Different contributions to the state of the art in reflectarray antennas for fixed and reconfigurable beams have been reviewed. A large variety of the reflectarray cells proposed to improve the antenna performance, as well as some broadband techniques have been presented.

Some selected recent and ongoing developments have been summarized. Examples such as contour-beam and multibeam reflectarrays, steerable-beam reflectarrays, dual-reflector antennas, reflectarrays in solar panels, deployable and inflatable reflectarrays have been presented. Finally, some challenging technologies and materials, such as 3-D printing, liquid crystals or graphene can be very promising for future applications in terahertz. The results presented here show a great potential of reflectarrays for passive and reconfigurable antennas in a large range of frequencies from microwaves to terahertz and even optical frequencies.

ACKNOWLEDGEMENTS

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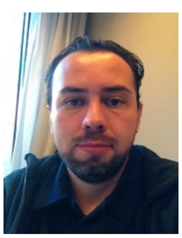

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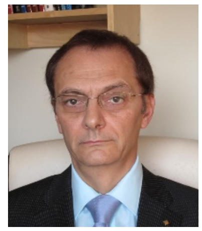

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