An X-Band Reflectarray With Novel Elements and Enhanced Bandwidth

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***Abstract*—A novel single-layer reflectarray element with an I-shaped dipole encompassed by a circular ring, showing smooth phase-frequency response, is proposed in this letter. Based on this element, an optimization method is adopted to match the desired phase delays at two edge frequencies so as to get fixed phase difference between two adjacent elements in the optimized band. A low-profile X-band 6 × 10-element reflectarray with a scattering angle of 30° for normal incidence of plane waves is designed and fabricated. Simulations and measurements show that a bandwidth of 22.3% for 3 dB directivity dropping and 15.2% for -10 dB sidelobe level (SLL) can be achieved.**

***Index Terms*—Bandwidth enhancement, optimization methods, reflectarrays.**

I. INTRODUCTION

PLANAR reflectarrays are rapidly becoming an attractive alternative to conventional parabolic reflectors due to their various advantages, such as being surface mountable with low mass and volume, easy deployment, and low manufacturing cost [1]. Although research on reflectarrays began in the 1960's, improvement on reflectarray bandwidth is still one of the most attractive works. For microstrip elements, their inherent narrowband behavior results in severe fluctuation in the phase response versus frequency as the operating frequency is slightly shifted from the center, consequently limiting bandwidth of the designed reflectarray. On the other hand, since the compensating phase for each element is designed at the center frequency by conventional method, different ray lengths from the feed to each point on the wavefront of the radiated beam result in different spatial phase delays, and phase errors caused by frequency excursion will occur in the reradiated phase front, which makes the cophase direction out of control [2]. For a large reflectarray, the latter case is more significant [3].

Several studies have been carried out to overcome the bandwidth limitation of the reflectarray. Thick substrate and multilayer structure are the most accessible ways to slow up the phase variation versus frequency and to improve the linearity of the phase-frequency characteristic of the elements [4]–[6], so as to broaden the bandwidth of reflectarray to about 20%. Based on the thick substrate and available linear phase characteristic, some optimization methods have been introduced in [7] and [8], in which several degrees of freedom of the element are tuned to simultaneously match the desired phase delays in a given frequency band. For a moderate-size reflectarray, the optimization method allows a significant bandwidth improvement. For instance, a 30% bandwidth was achieved for a reflectarray with the thickness of $0.127\lambda_0$ (λ_0 is the wavelength at the center frequency) in [8]. However, there are rarely published reflectarrays with low profile for wideband operation. A wideband reflectarray with the thickness of $0.0327\lambda_0$ was proposed in [9] and showed a bandwidth of 18%, and a novel element with delay lines was introduced. To further improve the bandwidth, only an element with a novel structure is not enough; the optimization method should be adopted at the same time.

In this letter, a novel element with smooth and approximately linear phase-frequency responses is presented, and a 6 × 10-element reflectarray illuminated by normal plane waves is designed by using the optimization method introduced in [8]. Four degrees of freedom are tuned to match the desired phase delays at two edge frequencies, so as to get parallel phase-frequency curves in the optimized band. A prototype is fabricated and measured, and good bandwidth performance is achieved with a low profile of $0.053\lambda_0$.

II. ELEMENT

The configuration of the proposed reflectarray element is shown in Fig. 1. The square unit cell has a side length $L = 10$ mm, and the outer radius of the ring is fixed to be $R_{\rm O} = 4.2$ mm for all elements in a reflectarray. By this way, abrupt geometry variations for neighboring cells in the conventional reflectarrays can be avoided, and almost equal mutual coupling between them can also be achieved, which is of benefit to the bandwidth improvement of a compact reflectarray [10].

Four degrees of freedom, i.e., the gap $W_{\rm S}$ between the circular ring and the I-shaped structure, the inner radius of the ring $R_{\rm i}$, the ratio $N = 0.5W_{\rm G}/(R_{\rm i} - W_{\rm S})$, and $M = 0.5W_{\rm B}/(R_{\rm i} - W_{\rm S})$, are introduced to control the phase distribution at different frequencies for optimization purpose. By varying the values of M and N, the resonant frequency of the I-shaped dipole can be adjusted very effectively. Meanwhile, the unit cell is etched on

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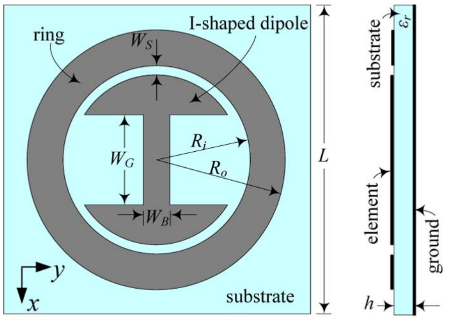


(a) (b)

Fig. 1. Geometry of the proposed element. (a) Top view. (b) Side view.

a substrate with a relative permittivity $\varepsilon_\mathrm{r} = 2.2$ and thickness $h = 1.5$ mm.

Assuming a plane wave polarized along the x-axis direction is normally incident on the element, a wide phase range of over 400° and smooth phase response can be obtained at the center frequency 10.5 GHz by tuning R_i from 1.5 to 3.5 mm, as shown in Fig. 2(a), as other parameters are optimal. Moreover, it can also be seen from Fig. 2(b) that the phase-frequency curves are approximately linear in a relatively wide frequency band around the center frequency, which is attributed to the slightly large ratio of the resonant frequencies of the I-shaped dipole and the ring. By tuning the four dimensional parameters R_i, W_S, M, and N, the length of current path on the ring and I-shaped dipole can be changed, which directly impact the resonant frequencies so as to change the amplitude and gradient of the phase delay versus frequency. Based on the achievable linear phase-frequency characteristic and several tunable parameters of the element, an optimization method can be implemented to further broaden the bandwidth, as discussed in Section III.

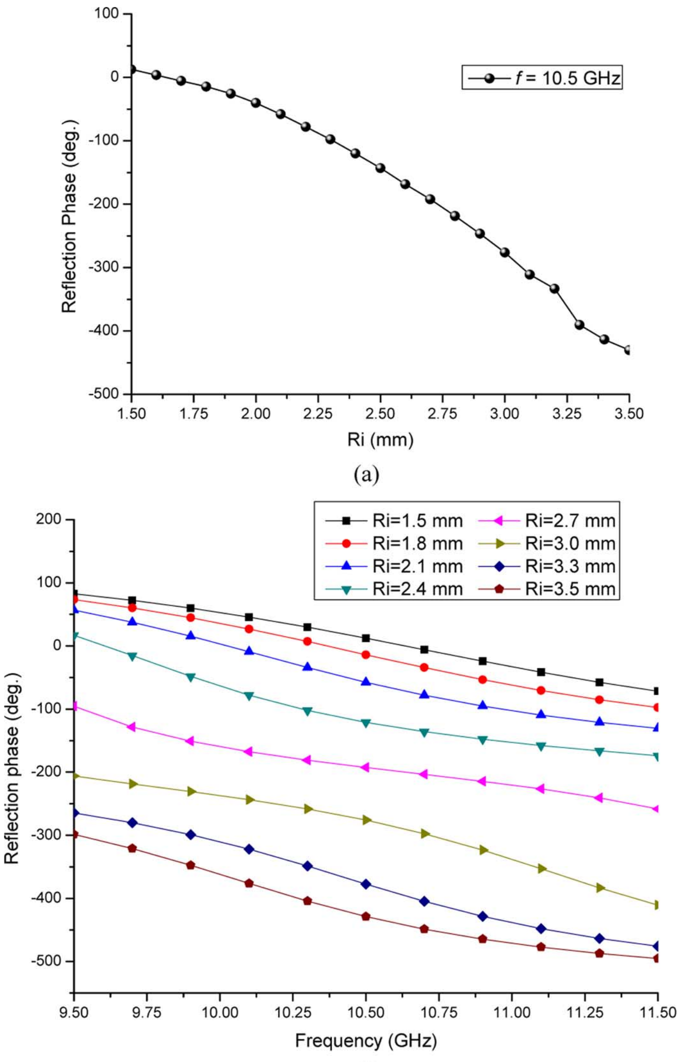
III. OPTIMIZATION METHOD BASED ON PROPOSED ELEMENT

For the conventional way to design a reflectarray, only the desired phase delays at the center frequency are tuned by one geometrical parameter, and it is difficult to predict the achieved reflection phases at the edge frequencies. In most cases, the phases deviate from the desired ones significantly. Therefore, if the phase delays are controllable in a band rather than *at a* single frequency, the bandwidth of the reflectarray can be broadened successfully.

In [8], a method to broaden the bandwidth of a single-layer printed reflectarray was proposed. The basic idea is to minimize the phase errors (differences between the desired and realized phases) at the center and two edge frequencies by choosing the optimum element parameters, and the error function is

$$e(m,n) = \sum_{i=\mathrm{l,c,u}} \left|\Phi^{\mathrm{desired}}(f_i)(m,n) - \Phi^{\mathrm{achieved}}(f_i)(m,n)\right| \tag{1}$$

where $\Phi^{\mathrm{desired}}(f_i)(m,n)$ and $\Phi^{\mathrm{achieved}}(f_i)(m,n)$ are the required and achievable phase delays, respectively, for the mth and nth elements at the frequency of f_i (l, c, and u represent lower, center, and upper frequency of the band). For the element, the difference of desired phase delay at two edge frequencies, $D_\mathrm{d}(f_\mathrm{u}, f_\mathrm{l}) = \Phi(f_\mathrm{u}) - \Phi(f_\mathrm{l})$, depends on the element location, and it is larger near the center of the reflectarray [7]. As we know, the effective way to increase the gradient of the phase delay is to make the resonant frequencies get closer, but for a thin substrate, the linearity of the phase-frequency curve could be seriously deteriorated as well. Therefore, the choosing principle of the desired phase delays in [8] is not appropriate for thin substrate that is used in this design.



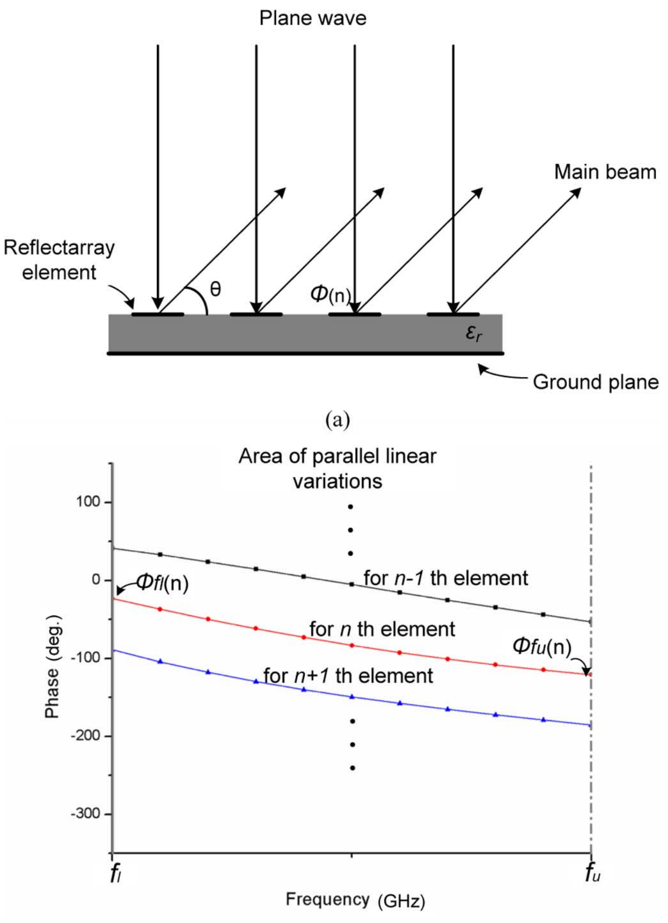
(a)

(b)

Fig. 2. (a) Reflection phase against R_i. (b) Phase delays versus frequency for different R_i. ($W_\mathrm{S} = 0.25$ mm, $M = 0.15$, $N = 0.5$, $R_\mathrm{O} = 4.2$ mm).

Here, a two-frequency-matching method is presented based on the preceding element. By taking advantage of the linear phase-frequency response of the element, optimization at only two edge frequencies f_l and f_u can work well. Four degrees of freedom of the element—R_i, W_S, M, and N—are properly chosen to minimize the difference between the desired and realized phases at f_l and f_u, and the desired phase delays should fulfill the following equation:

$$\Phi(f_\mathrm{l})(n) - \Phi(f_\mathrm{l})(n+1) = \Phi(f_\mathrm{u})(n) - \Phi(f_\mathrm{u})(n+1). \tag{2}$$



(a)

(b)

Fig. 3. (a) Profile view of a reflectarray illuminated by plane wave. (b) Phase versus frequency for three typical elements.

TABLE I
SETUP OF PARAMETRIC SWEEPING

parameters	R_i (mm)	W_S (mm)	M	N
values	1.5 - 3.5 step: 0.05	0.15 - 0.35 step: 0.05	0.1 - 0.2 step: 0.05	0.4 - 0.6 step: 0.05

The value of the equation is the desired phase delay difference between the nth and $(n+1)$th element at center frequency in Fig. 3(a), which is determined by the lattice size and the beam-scanning angle. It is to say that, similar to the situation in [4], the goal of the introduction of (2) is to make the phase-frequency responses of the elements in a reflectarray be a cluster of parallel curves over the frequency band from f_l to f_u, as shown in Fig. 3(b), and the distinction is that the parallel phase curves are realized by tuning only one dimension parameter in [4] while tuning four dimension parameters in this design. Therefore, the phase difference between two adjacent elements is almost fixed in the optimized band, and the sidelobe level (SLL) of the radiation pattern could remain low, although theoretically the beam-scanning angle shifts in a very small range.

Beforehand, a database including all reflection phase responses of each element with different $(R_\text{i}, W_\text{S}, M, N)$ at f_l and f_u should be built by parametric sweeping in HFSS, and the sweeping setup is shown in Table I. It is worth noting that the sweeping parameter W_S, M, and N are not deviated away from the previous optimized ones too much so as to ensure the linearity of the phase-frequency response. Subsequently, a simple program can help to find out the optimal parameters $(R_\text{i}, W_\text{S}, M, N)$ to make sure the achieved phases as close to the desired values as possible.

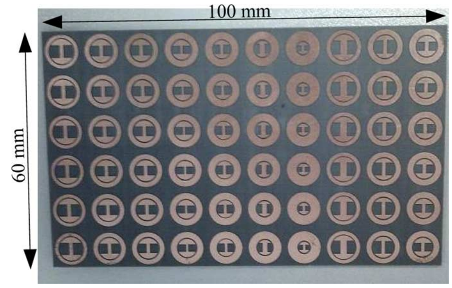


Fig. 4. Photograph of the fabricated reflectarray.

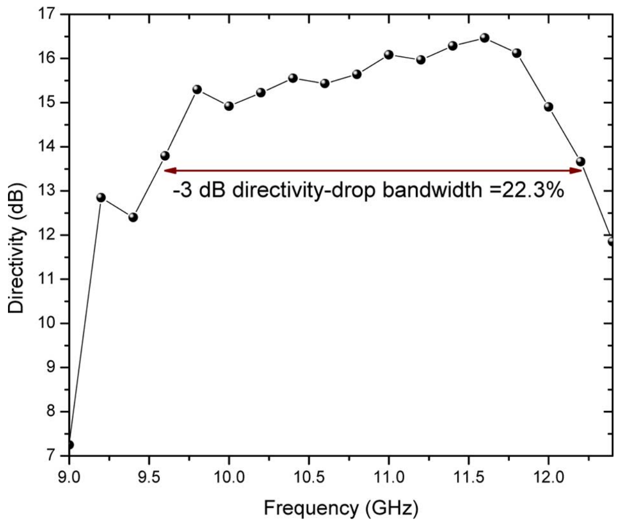
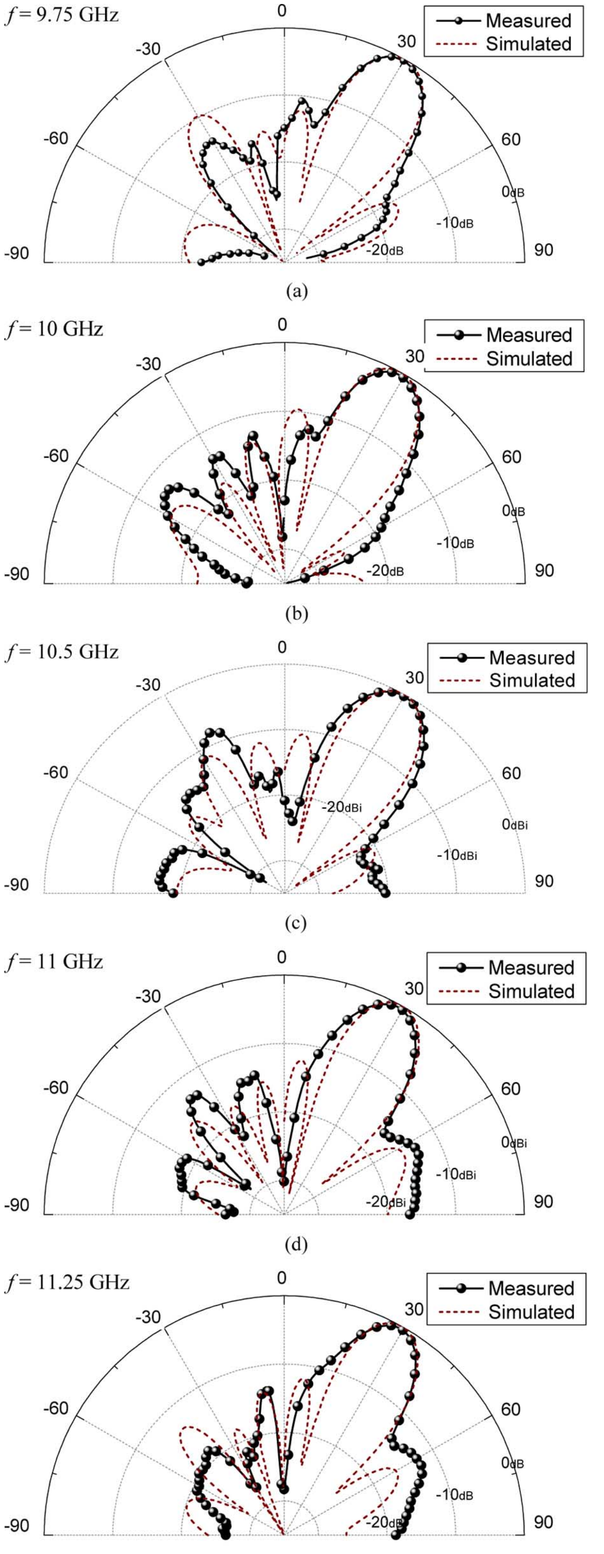


Fig. 5. Simulated directivity of the reflectarray versus frequency.

IV. RESULTS

A 6 × 10-element reflectarray with a scattering angle of 30° for normal incidence of plane waves is designed and fabricated to validate the availability of the proposed element. The photograph of the fabricated prototype is shown in Fig. 4. Since the main beam is scanned in the xoz-plane, the dimensions of the elements in a column are the same with each other. In the measurement system, large distance from the feeder to reflectarray is adopted to simulate the plane wave, and only a small part of energy is intercepted by the reflectarray. Therefore, only normalized radiation patterns can be deduced from the tested results. A simulated -3-dB directivity-drop bandwidth of 22.3% is achieved when the reflectarray is centered at 10.5 GHz and the two predetermined edge frequencies f_l and f_u are 10 and 11 GHz, as shown in Fig. 5. The directivity at 10.5 GHz is 15.5 dB, and the computed aperture efficiency is 38.5%. Due to four degrees of freedom tuned to match the desired phase delays in the optimized band, a -10-dB SLL bandwidth of 15.2%,



(a) (b) (c) (d) (e)

Fig. 6. Radiation patterns at five typical frequencies. (a) 9.75 GHz. (b) 10 GHz. (c) 10.5 GHz. (d) 11 GHz. (e) 11.25 GHz.

ranging from 9.75 to 11.35 GHz, is achieved. The radiation patterns at five typical frequencies are presented in Fig. 6, in which measured results show good agreement with simulations. It is noted that the differences between the measured and simulated results are attributed to the frequency limitation of the substrate whose manufacturer specifies to be below 10 GHz, and the fabrication tolerance is another account of the differences.

V. CONCLUSION

This letter presents a novel reflectarray element, and a corresponding X-band reflectarray is designed, fabricated, and measured. An optimization method is adopted by making use of several degrees of freedom to match the desired phase delays in a band. A -3-dB directivity-drop bandwidth of 22.3% and -10-dB SLL bandwidth of 15.2% are obtained in spite of using a thin substrate. Comparatively, few reported reflectarrays with low-profile substrate can be found to reach the gain bandwidth of 20%.

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