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"Design and Optimization of Periodic Antenna Arrays for Grating-Lobe Suppression and Improved Radiation Performance"

Shankar Kumar[1], Dr. Anil Kumar[2]

[1]Research Scholar, Reg. No. Phy-2206/22, Dept. of Physics BNMU Madhepura

[2]Associate Professor. Dept. of Physics, R.J.M. College, Saharsa, BNMU Madhepura

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ABSTRACT

Periodic antenna arrays are widely employed in modern wireless communication, radar, satellite communication, and sensing systems because of their ability to provide high directivity, beam steering, and flexible radiation control. However, the use of periodic element spacing can produce grating lobes when the inter-element spacing becomes electrically large, particularly during wide-angle beam steering. These unwanted radiation maxima can reduce antenna efficiency, create angular ambiguities, and degrade overall system performance. This research presents the design and optimization of a periodic antenna array aimed at suppressing grating lobes while improving key radiation characteristics. The proposed approach investigates the effects of element spacing, excitation amplitude, progressive phase distribution, element geometry, and mutual coupling on the far-field radiation pattern. Analytical array-factor calculations are combined with full-wave numerical electromagnetic analysis to evaluate the performance of the proposed configuration. The study further investigates the influence of array spacing and beam-steering angle on grating-lobe formation and scan performance. The proposed design methodology provides an effective trade-off between grating-lobe suppression, aperture utilization, radiation efficiency, and implementation complexity. The results demonstrate that appropriate optimization of the periodic lattice and excitation parameters can significantly improve the radiation performance of phased antenna arrays.

Keywords: Grating lobes, element spacing, beam steering, periodic lattice, phased antenna arrays.

INTRODUCTION

Antenna arrays have become an essential technology in modern wireless communication, radar, satellite communication, remote sensing, navigation, and sensing systems because they provide high directivity, beam steering, and flexible radiation-pattern control [1]. By combining the electromagnetic fields produced by multiple radiating elements, an array can generate a narrow and electronically steerable main beam with improved gain and angular resolution compared with many single-element antennas [2]. Among different array configurations, periodic antenna arrays, in which elements are arranged at regular spatial intervals, are particularly attractive because of their simple geometry, predictable electromagnetic behavior, and ease of fabrication. However, their periodic nature can also introduce unwanted radiation phenomena, especially grating lobes [3]. These are additional radiation maxima that occur when the inter-element spacing and operating wavelength satisfy specific spatial phase conditions. They become particularly significant when the element spacing is relatively large or when the main beam is scanned over wide angular regions. The presence of strong grating lobes can distribute radiated power away from the desired direction, reduce effective gain, increase

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interference, and produce angular ambiguities in radar and communication systems. Therefore, effective grating-lobe suppression is a critical requirement in the design of high-performance electronically scanned antenna arrays [4].The design challenge involves achieving an appropriate balance among element spacing, array dimensions, excitation amplitude, phase distribution, scanning range, gain, side lobe level, beam width, and radiation efficiency. Conventional methods based only on reducing element spacing can suppress grating lobes but may increase the number of array elements, mutual coupling, feeding complexity, and overall system cost [5]. Consequently, optimization-based design strategies provide an attractive alternative. This research focuses on the design and optimization of periodic antenna arrays to suppress grating lobes while improving overall radiation performance. The proposed approach considers controlled element spacing, optimized amplitude and phase excitation, and suitable array configuration to obtain a strong main beam with reduced unwanted radiation. The resulting methodology provides a practical foundation for developing high-directivity, wide-angle scanning antenna arrays for advanced radar, wireless communication, satellite, and sensing applications.

GENERATION OF GRATING-LOBE IN PERIODIC ARRAYS

Grating lobes are unwanted radiation maxima that arise in periodic antenna arrays when the spatial sampling interval between adjacent elements becomes sufficiently large relative to the operating wavelength. They are produced by constructive interference among the electromagnetic fields radiated by individual array elements in directions other than the intended main-beam direction [6]. Unlike ordinary side lobes, grating lobes can have relatively high radiation levels and may approach the magnitude of the main beam, significantly affecting the performance of beam-steering systems. Grating-lobe formation becomes more severe as the element spacing increases and during wide-angle electronic beam steering [7]. A commonly adopted design principle for avoiding grating lobes over broad scanning conditions is to maintain the element spacing close to or below half a wavelength. In addition to spacing, excitation amplitude, phase distribution, array dimensions, and mutual coupling can influence grating-lobe levels [8]. Therefore, an effective design must consider these parameters collectively to achieve low grating-lobe radiation, high gain, narrow beam width, and reliable wide-angle scanning performance.

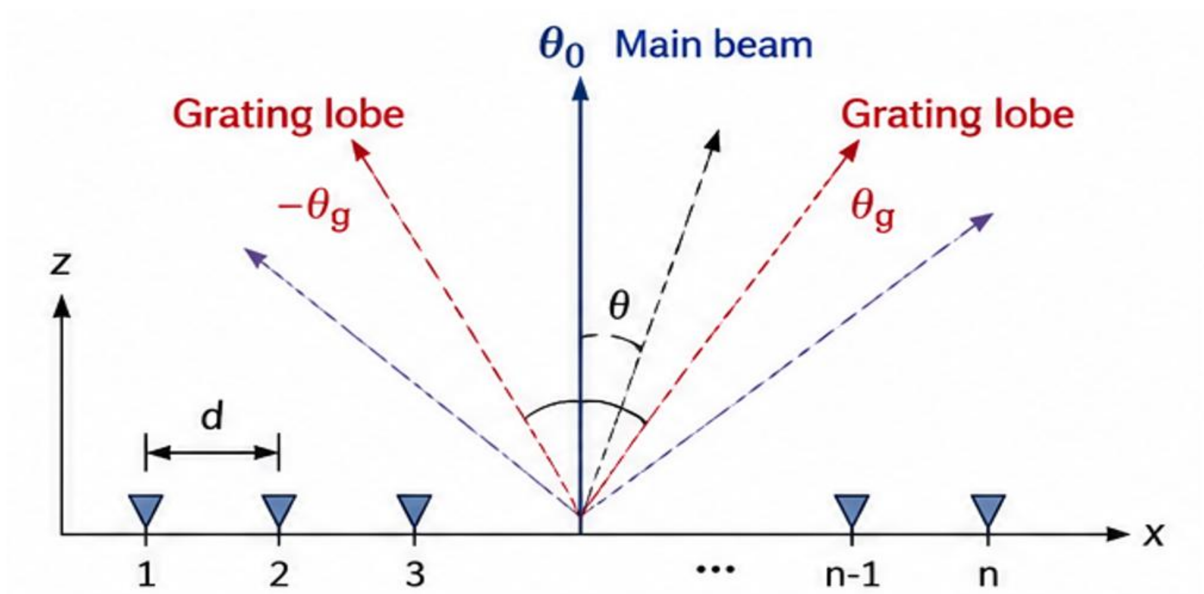

Fig.-(1) Periodic Linear Array

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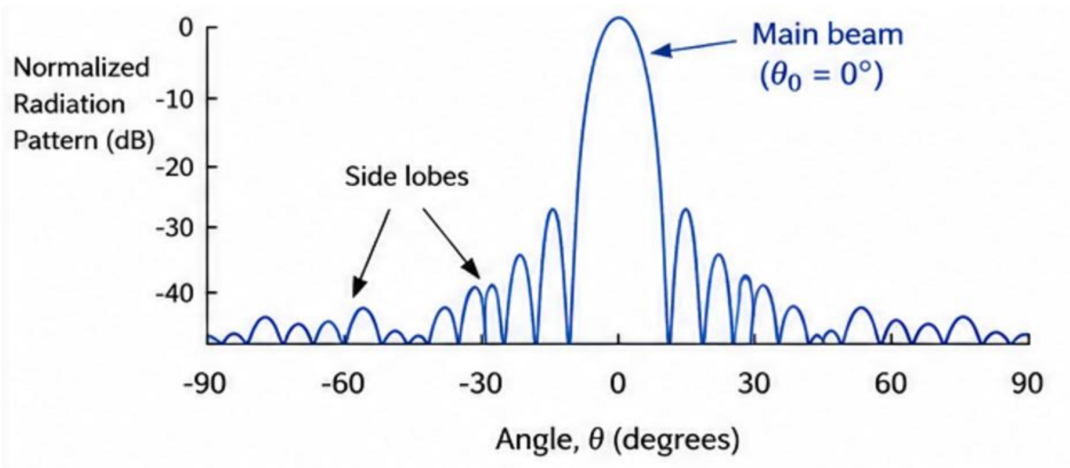

Fig.-(2) No Grating Lobe

The array factor of an *N*-element periodic linear array is

$$AF(\theta) = \frac{\sin\left[\frac{N}{2}(kd\sin\theta + \beta)\right]}{\sin\left[\frac{1}{2}(kd\sin\theta + \beta)\right]}$$

Where, $k = \frac{2\pi}{\lambda}$ =Wave number, d =Inter-element spacing, β =Progressive phase shift between adjacent elements, N =Number of antenna elements, θ =Observation angle. The maxima (lobes) occur when $(kd\sin\theta + \beta) = 2m\pi$, where $m = 0, \pm 1, \pm 2, \cdots$ For broadside array, $= 0$. Hence, $\frac{2\pi d}{\lambda}\sin\theta = 2m\pi$

or, $\sin\theta_m = \frac{m\lambda}{d}$. The first possible grating lobe corresponds to $= \pm 1$. Thus, $\sin\theta_{\pm 1} = \pm\frac{\lambda}{d}$. For no grating lobe, $|\sin\theta_{\pm 1}| = \left|\frac{\lambda}{d}\right| > 1$. Therefore, $< \lambda$.

To guarantee that no grating lobe appears over the entire visible region and during beam scanning, the standard design criterion is $\left(d \leq \frac{\lambda}{2}\right)$, which corresponds to Fig.-(2) .

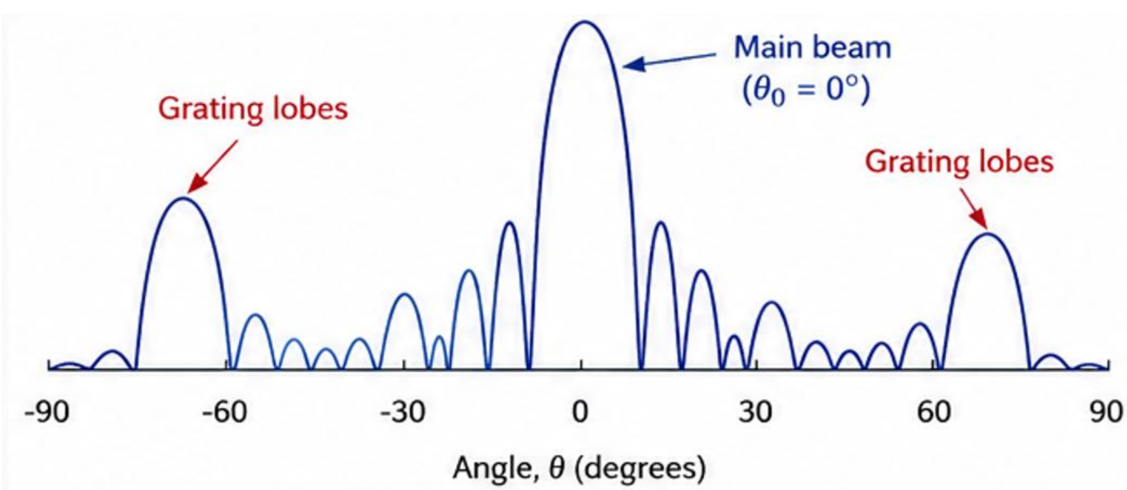

Fig.-(3) With Grating Lobe

Again, $\sin\theta_m = \frac{m\lambda}{d}$. If $d > \lambda/_2$, the spacing becomes sufficiently large that higher-order maxima begin approaching the visible region. When $|\sin\theta_m| \le 1$, additional maxima appear. For $m = \pm 1$, $\theta_g = \sin^{-1}\left(\frac{\lambda}{d}\right)$ which represents the first grating lobe. Similarly, $\theta_m = \sin^{-1}\left(\frac{m\lambda}{d}\right)$, $m = \pm 1, \pm 2, \cdots$ provided

$\frac{m\lambda}{d} \le 1$. Therefore, $\left(d > \lambda/_2\right) \Rightarrow$ Additional grating lobes appear symmetrically about the main beam, which corresponds to Fig.-(3) .

PROPOSED PERIODIC STRUCTURE AND DESIGN

The proposed antenna configuration is a periodically arranged planar array designed to achieve reduced grating-lobe levels while maintaining high gain, directivity, and efficient beam steering. The structure consists of identical radiating elements positioned on a regular two-dimensional grid along the x-axis and y-axis as shown in fig.-(4). A rectangular periodic arrangement is selected because it provides a simple geometry, predictable radiation characteristics, and practical suitability for fabrication and integration with modern phased-array systems [9]. The inter-element spacing is carefully determined based on the desired operating frequency and the maximum beam-steering angle to ensure optimal array performance. The inter-element spacing is carefully optimized based on the desired operating frequency and the maximum beam-steering angle to ensure efficient array performance. Amplitude tapering is incorporated to reduce side lobe levels, while optimized phase excitation is used to direct the main beam toward the desired observation angle as shown in fig.-(5).

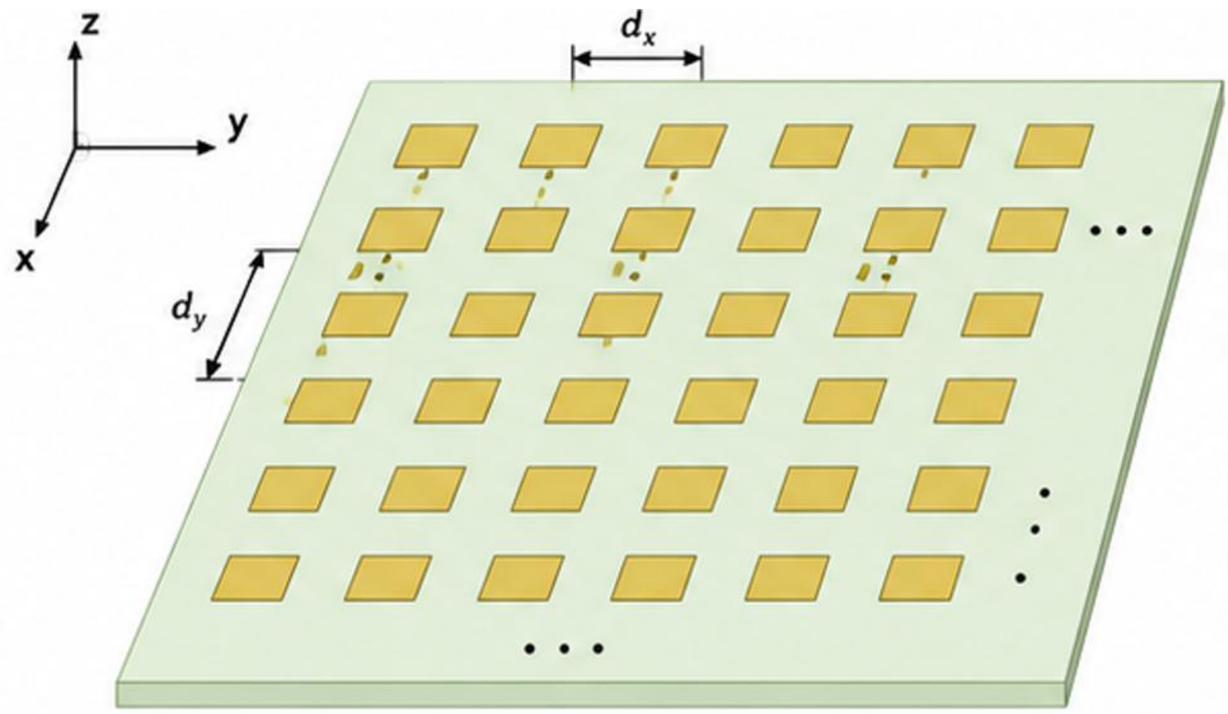

Fig.-(4) Regular 2-D Planar Antenna Array

A parametric optimization procedure is proposed in which element spacing, excitation amplitude, phase progression, and array dimensions are systematically varied. The optimization objective simultaneously accounts for grating-lobe suppression, side-lobe reduction, realized gain enhancement, beam width control, and

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radiation efficiency to achieve an overall high-performance antenna array design [10]. The resulting optimized periodic structure is expected to provide a strong main beam, reduced unwanted radiation, improved directivity, and enhanced wide-angle beam-steering capability while retaining the manufacturing advantages of regular array geometry.

LOBE SUPPRESSION TECHNIQUES

Effective suppression of grating lobes is essential for improving the radiation performance and scanning capability of periodic antenna arrays [11]. Several techniques can be employed individually or in combination to minimize unwanted radiation while preserving high gain and directivity.

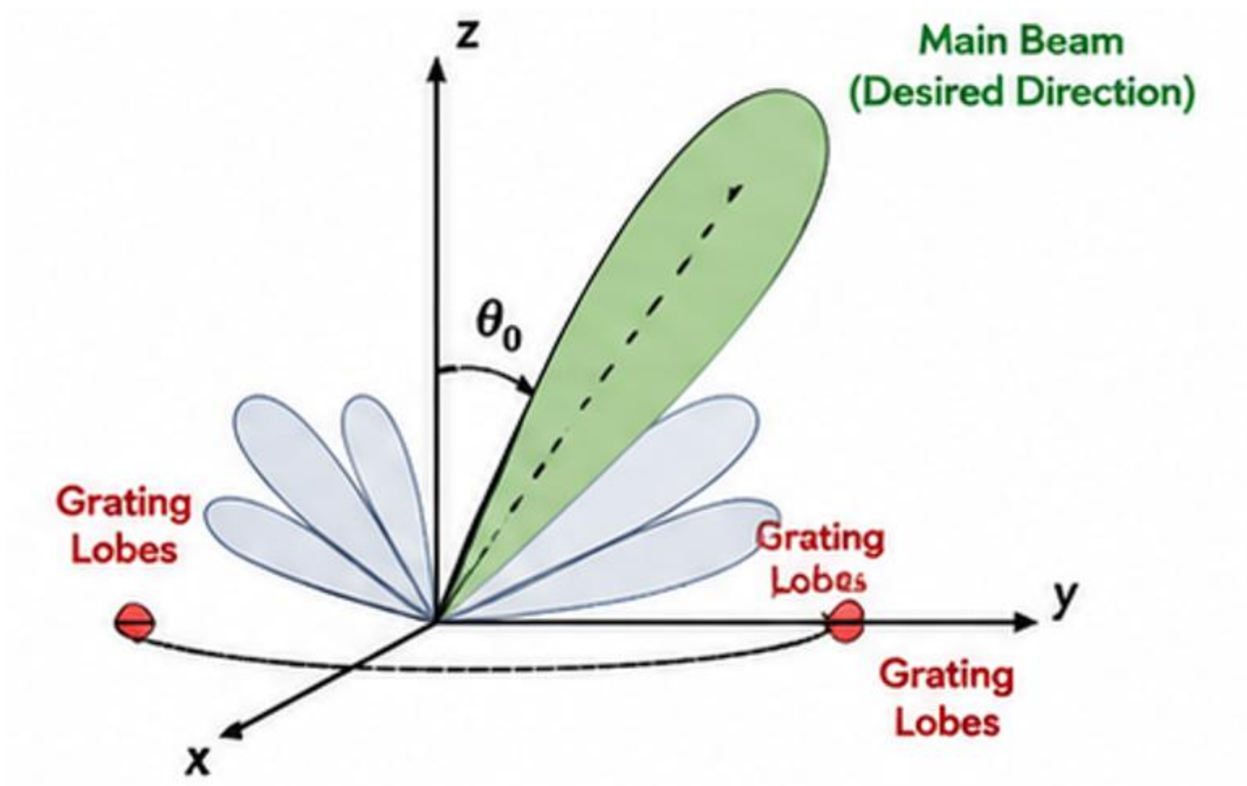

Fig.-(5) Beam Steering (Amplitude tapering reduces side lobes Optimized phase excitation steers the main beam toward the main angle (θ_0, ϕ_0))

The most fundamental approach is to optimize the inter-element spacing. Maintaining the element separation at an appropriate fraction of the operating wavelength reduces the possibility of higher-order spatial modes entering the visible region [12]. However, excessively small spacing may increase mutual coupling and fabrication complexity; therefore, spacing must be selected according to the required scanning range and operating frequency. In this method, the excitation amplitude of the array elements is varied according to optimized distributions such as Taylor, Chebyshev, cosine, or binomial weighting. Lower excitation levels toward the edges of the aperture can significantly reduce side lobe levels. Although tapering may slightly broaden the main beam and reduce peak gain, an optimized distribution provides a suitable compromise between side lobe suppression and radiation efficiency. Phase optimization can also be applied to modify the interference conditions among array elements [13]. By controlling the progressive phase excitation, the main beam can be accurately directed toward the desired scanning angle while minimizing unwanted secondary maxima. Sub-

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arraying and element-pattern engineering provide further degrees of freedom for radiation-pattern control. Properly designed sub-arrays can distribute the aperture excitation more effectively, while directional element patterns can attenuate radiation in unwanted angular regions. Finally, numerical optimization algorithms such as genetic algorithms, particle swarm optimization, differential evolution, and other evolutionary techniques can simultaneously optimize spacing, amplitude, phase, and element positions. A multi-objective optimization strategy can therefore achieve low grating-lobe levels, reduced side lobes, high gain, narrow beam width, and improved wide-angle scanning performance [14].

IMPROVED RADIATION PERFORMANCE

The optimization of periodic antenna arrays for grating-lobe suppression directly contributes to improved overall radiation performance. A well-designed array should not only minimize unwanted radiation maxima but also maintain high gain, directivity, radiation efficiency, narrow beam width, and stable beam-steering characteristics. These parameters are strongly influenced by element spacing, excitation amplitude, phase distribution, array aperture, and mutual coupling between neighboring elements. One of the major improvements obtained through the proposed optimization is enhanced directivity. By directing a larger portion of the radiated electromagnetic energy toward the intended direction, the optimized antenna array enhances the strength of the main radiation beam while minimizing energy leakage into undesired side and grating lobes [15]. Appropriate amplitude tapering reduces the contribution of peripheral elements and suppresses unwanted radiation outside the main beam. An optimized weighting function can provide an effective balance between beam width and side lobe suppression. Another important performance improvement is enhanced wide-angle beam steering. The proposed array can be evaluated at different steering angles to verify whether the main beam remains accurately directed toward the desired position without producing significant grating lobes. Furthermore, optimization of element spacing and excitation parameters can help manage mutual coupling and improve impedance stability across scanning conditions. Key performance indicators—including realized gain, half-power beam width, side lobe level, grating-lobe level, radiation efficiency, and scanning range-should therefore be evaluated collectively. Overall, the optimized periodic array provides a balanced radiation pattern with a strong main beam, reduced unwanted lobes, improved directivity, and reliable scanning performance, demonstrating its potential for high-performance electronically steerable antenna systems.

COMPARISON WITH OTHER RELATED APPROACHES

The performance of the proposed optimized periodic antenna array can be compared with conventional uniform arrays, non-uniform arrays, sparse arrays, random arrays, and optimization-based array configurations. Each approach offers specific advantages in controlling grating lobes, side lobes, gain, beam width, and beam-steering capability. A conventional uniformly spaced array is simple to design, easy to fabricate, and provides predictable radiation characteristics. However, when the inter-element spacing becomes relatively large or the beam is scanned over wide angles, strong grating lobes may appear. Therefore, its scanning performance is limited by the spatial periodicity of the array. Non-uniform arrays modify the element positions to disturb the periodic phase relationship responsible for strong unwanted radiation maxima. Such configurations can provide effective grating- and side lobe suppression, but their irregular geometry may increase design complexity and introduce additional manufacturing constraints. Nevertheless, sparse configurations require sophisticated optimization because increased element spacing can generate grating lobes and high side lobe levels. Similarly, sub-array-based approaches reduce feeding-network complexity but may introduce sub-array-level grating lobes. In comparison, the proposed optimized periodic array retains the structural simplicity and regularity of conventional periodic arrays while incorporating optimized element spacing, excitation amplitude, and phase distribution . This provides a balanced solution for reducing unwanted radiation without completely abandoning periodic geometry. The approach is therefore expected to offer improved gain, lower grating-lobe and side lobe levels, and enhanced wide-angle beam steering with moderate implementation complexity. Consequently, the proposed design represents a practical compromise between radiation performance, optimization flexibility, manufacturing simplicity, and system integration, making it suitable for advanced radar, wireless communication, satellite, and sensing applications.

APPLICATIONS

Optimized periodic antenna arrays with effective grating-lobe suppression have significant potential in modern wireless communication, radar, sensing, navigation, and remote-sensing systems. Their capability to produce high-gain beams with electronic beam steering, while effectively suppressing unwanted radiation, makes them highly suitable for applications that demand precise directional control and broad-angle beam scanning. One of the most important applications is phased-array radar . Radar systems require narrow and rapidly steerable beams for target detection, tracking, and angular localization. Strong grating lobes can generate ambiguous target responses and reduce detection accuracy. The proposed optimized array can minimize unwanted radiation and improve angular resolution, making it suitable for surveillance, weather, air borne, and multifunction radar systems. In 5G and 6G wireless communication, antenna arrays are increasingly used at millimeter-wave and sub-terahertz frequencies to compensate for propagation losses through highly directional beam forming. Grating-lobe suppression enables reliable beam steering while reducing interference with users located in undesired directions. Consequently, optimized periodic arrays can contribute to improved coverage, spectral efficiency, and link reliability. The proposed array architecture is also applicable to automotive radar for vehicle detection, collision avoidance, adaptive cruise control, and advanced driver-assistance systems. They can also be applied to radio astronomy, navigation systems, electronic warfare, spectrum monitoring, and wireless localization. The combination of high directivity reduced grating lobes, controlled side lobes, and wide-angle beam steering makes optimized periodic antenna arrays a promising technology for next-generation electromagnetic systems. Their relatively regular geometry also supports practical fabrication, calibration, and integration into compact electronically steerable platforms.

CONCLUSIONS

This research has presented a systematic design and optimization approach for periodic antenna arrays with the primary objective of suppressing grating lobes and improving overall radiation performance. Grating lobes represent a major limitation in periodically spaced antenna arrays, particularly when the inter-element spacing is relatively large or when electronic beam steering is performed over a wide angular range. Their suppression is therefore essential for achieving reliable, high-directivity, and electronically steerable antenna systems. The proposed design strategy focuses on optimizing important array parameters. Appropriate control of element spacing reduces the possibility of higher-order spatial modes entering the visible region, while optimized amplitude and phase excitation improves the distribution of electromagnetic energy across the aperture. These techniques can simultaneously reduce unwanted grating and side lobe radiation while maintaining a strong main beam. The analysis also demonstrates that radiation performance should not be evaluated using a single parameter. An optimized periodic configuration can provide an effective compromise between high gain, narrow beam width, low unwanted radiation, and wide-angle beam steering. Compared with conventional uniform, random, sparse, and non-uniform arrays, the proposed approach retains the structural simplicity and manufacturing advantages of periodic geometry while providing additional flexibility for radiation-pattern control. Future investigations should include full-wave electromagnetic simulations and experimental measurements to validate the proposed design under realistic operating conditions. Overall, the proposed optimization methodology provides a practical foundation for developing high-performance periodic antenna arrays with reduced grating lobes and improved radiation characteristics.

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