Recent Advances in the Modeling of Periodic Leaky-Wave Antennas Scanning Through Broadside

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I. INTRODUCTION

Periodic leaky-wave antennas (LWAs) have been studied for several decades. Compared to uniform LWAs, the first of which was invented by Hansen in 1940 [1], periodic LWAs are capable of backward and forward radiation, using a space harmonic of the periodic spectrum of the structure. Their main weakness has been the issue of poor radiation around broadside, due to the resonance of the structure at this frequency, where the phase constant of the space harmonic used for radiation goes to zero.

In recent years, with advent of metamaterial structures, LWAs have known a regain of interest. Much progress has been made in LWA theory, structures and systems. This progress has not been restricted to metamaterial LWAs but has also pertained to other types of periodic LWAs [2], [3], [4]. Particularly, the broadside issue has been studied for different antenna types and from different perspectives [5], [6], [7], [8].

This paper is a review on the recent advances in this area. Specifically, it presents a generalized equivalent transmission line modeling approach and provides a general methodology for efficient broadside radiation based on the aforementioned contributions in combination with our recent work in [9], [10], [11].

II. GENERALIZED EQUIVALENT TRANSMISSION LINE MODELING OF PERIODIC LEAKY-WAVE ANTENNAS

In [10], we have shown that most periodic LWAs, although they may be topologically quite different, share qualitatively similar responses, and we have illustrated this point by comparing a series-fed patch LWA, a phase-reversal LWA and a composite right/left-handed (CRLH) LWA. These LWAs have in common the following features: i) they use a space harmonic for radiation, ii) this radiating space harmonic generally exhibits a stop-band at its zero phase frequency, iii) this stop-band can be closed up, if proper conditions are satisfied (main topic of this paper), iv) the radiating space harmonic has a quasi-linear dispersion around the broadside frequency. The differences between different periodic LWAs are purely quantitative, and may include: i) the electrical size of the unit cell period p, ii) the group velocity v_g or slope of the \( \omega - \beta \) curve of the radiating space harmonic, iii) the subsequent scanning sensitivity with frequency, and iv) the specific radiating space harmonic, which may be typically either \( n = -1 \) or \( n = 0 \). Based on their qualitative similar behavior and despite their quantitative differences, these LWAs may be modeled and understood by a unified approach, that is referred to as the generalized equivalent transmission line modeling.

III. BROADSIDE RADIATION ISSUES

If no specific design precautions have been taken, periodic LWAs experience strong variations in the phase constant (space harmonic \( \beta_n \)) and attenuation constant (leakage factor \( \alpha \)) around the broadside frequency-angle point. Hence, the matching as well as the aperture distribution strongly varies around this point. This affects the beam width and the gain, which are generally severely degraded, up to the point of making the antenna unusable in this practically crucial frequency.

We shall briefly review the pathological symptoms of periodic LWA broadside radiation and systematically propose remedies to the issues at their origin, following a four-step procedure. This procedure will ultimately lead to an optimized design characterized by frequency-independent parameters, including the input impedance, the leakage factor and the gain across broadside, for seamless and efficient scanning in the entire angular sector of interest of the LWA.

IV. FOUR-STEP PROCEDURE SOLVING THE BROADSIDE RADIATION ISSUE

The four-step procedure consists in satisfying four conditions.

A. First Condition: Series and Shunt Radiators – Non-Zero Leakage Factor at Broadside

In [6], it has been shown that that in a CRLH LWA the leakage factor at broadside reads \( \alpha = \sqrt{RG/p} \), where R and G are the series and shunt resistance and conductance, respectively, of the equivalent circuit model of the structure, and it has been deduced that both series and shunt radiation contributions were required for achieving \( \alpha \neq 0 \) at broadside. This is a fundamental requirement for broadside radiation in a periodic LWA, which has been generalized in [10] to arbitrary periodic LWAs, using the aforementioned generalized transmission line modeling approach.
B. Second Condition: Frequency-Balancing – Closure of the Stop-Band

The frequency-balancing condition $\omega_{se} = \omega_{sh}$, where $\omega_{se}$ and $\omega_{sh}$ denote the series and shunt resonances, respectively, of the periodic structure, was initially developed in the context of CRLH metamaterials [12], where it was shown to allow efficient broadside radiation in a CRLH LWA. Using the generalized transmission line modeling, this condition was recently extended to arbitrary periodic LWAs [10].

C. Third Condition: $Q$-Balancing – Frequency Independent Leakage Factor

Although frequency-balancing closes up the open stop-band, it generally leaves out a strong $\alpha$ variation around broadside, with a drop at broadside, which translates into mediocre broadside gain and frequency-dependent gain through broadside. To eliminate this variation, the radiation contributions, $R$ and $G$, have to be properly adjusted. The corresponding condition is referred to as the $Q$-balancing condition. This condition stipulates that the quality factors of the series resonance element, $Q_{se}$, and the quality factor of the shunt resonance element, $Q_{sh}$, have to be equal, $Q_{se} = Q_{sh}$. This condition is identical to the Heaviside condition for distortion-less uniform lossy transmission lines, but is extended here to the problem of periodic radiative (or also lossy) structures. It has been simultaneously reported in [8] and [10], for the CRLH case and for arbitrary periodic LWAs, respectively.

D. Fourth Condition: Common Series and Shunt Radiation Direction

Very recently, it has been shown that radiation emanating from the shunt elements in a longitudinally symmetric LWA vanishes at broadside [11]. This is due to the fact that such a structure supports oppositely directed transverse currents, whose radiative contributions cancel out in the far field. As a consequence, the radiation conductance $G$ reduces to zero, which limits the radiation efficiency of the LWA to a theoretical maximum of 50%. This issue can be resolved by introducing longitudinal asymmetry in the structure, avoiding opposite current and henceforth allowing efficient shunt broadside radiation.

V. Conclusion

It has been shown, mainly based on a generalized equivalent transmission line model for periodic structures, which may be interpreted as an extension of the CRLH modeling techniques, that the poor broadside radiation issue in periodic LWAs can be solved by following four fundamental conditions.

REFERENCES