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An Overview of the Truncated Floquet Wave Diffraction Theory

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Introduction

This paper summarizes the research activities conducted at the University of Siena during the past 10 years on the truncated Floquet wave diffraction theory under the continuous guidance of Professor Felsen, recently passed away. The authors, all belonging to the University of Siena, have interacted with Professor Leopold B. Felsen on various topics in the same framework. For lack of space, this paper selects a few sample of those topics dearest to Professor Felsen. Sadly, the group of authors does not include Professor Roberto Tiberio, leader of the group in Siena and sincere friend of Professor Felsen, who passed away a few months ago.

In a systematic sequence of previous studies [1]-[13], we have explored methods (in both the frequency and time domains) to reduce the often prohibitive numerical efforts in element-by-element full-wave analysis of large truncated planar periodic phased arrays, either in free-space [1]-[9] or in presence of dielectric configurations [11]-[13]. In our approach, the element-by-element space domain array Green's function (AGF) for a planar periodic phased array of dipoles (the basic building block for modeling practical phased arrays) is restructured into an alternative "collective" physics-based spectral domain formulation that parameterizes the field radiated from the elementary dipoles in terms of the radiation from a superposition of continuous truncated Floquet Wave (FW)-matched source distributions extending over the entire aperture of the array, with inclusion of other truncation-induced Floquet-modulated wave types. Since the FW series exhibits excellent convergence properties when the observation point is located far enough away from the array surface so as to render evanescent FWs and the corresponding diffracted fields negligible, this representation has been found to be more efficient than the direct summation over the spatial contributions from each element of the array, especially when each FW aperture distribution is treated asymptotically. Preliminary to the treatment of rectangular array geometries have been our investigations on semi-infinite [1] and right-angle sectoral [2], [3] planar phased arrays of dipoles with equi-amplitude excitation, as well as strip arrays with one-direction-tapered illumination [4].

Free space rectangular array Green's function: frequency domain

For the FD parameterization, the species of FW-induced diffracted rays are shown in Fig. 1 for an array of elementary dipoles (a) in free-space and (b) on a grounded infinite dielectric slab. FW-induced spherical and conical diffracted ray congruences emanate from the array corners and edges, respectively. For the slab configuration, in addition, surface plane- and cylindrical-waves are excited at the edges and corners of the array, respectively. The direction of propagation of surface edge waves

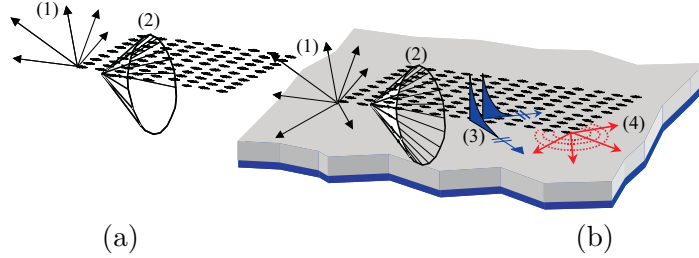


Figure 1: Rays excited by Floquet waves due to a finite array of elementary dipoles in (a) free-space and (b) printed on a grounded dielectric slab. (1) spherical vertex-excited (space) diffracted wave, (2) conical edge-excited (space) diffracted wave, (3) planar edge-excited surface wave, (4) cylindrical vertex-excited surface wave.

is such as to match the phase velocity of the dominant FW along the edges. For a large planar rectangular phased array of dipoles in free-space, with weakly varying amplitude excitation and linearly varying phase, the formulation generalizes the one in [2],[3] for uniform illumination, and it is detailed in [5]. The uniform-excitation AGF assumes its most intricate form in the vicinity of a vertex, with transition and compensation mechanisms that have been quantified analytically, interpreted phenomenologically, and computed efficiently, with accuracy validated through a preliminary set of numerical simulations. The AGF of the canonical finite planar phased array of dipoles with tapered excitation is constructed by plane wave spectral decomposition in the two-dimensional complex wavenumber domain corresponding to the array-plane coordinates. This is followed by manipulations and contour deformations that prepare the integrand for subsequent efficient and physically incisive asymptotics, parameterized by critical spectral points, i.e., saddle points and singularities. The critical points define the asymptotic behavior of the edge and vertex diffracted rays; the confluence of these critical points in transition regions determines a variety of locally uniform new transition functions for truncated edge diffracted and vertex diffracted waves. When combining the asymptotic contributions from the four vertices of a rectangular array, we obtain the sum of asymptotic uniform contributions related to locally amplitude-modulated truncated FWs (FW-excited diffracted rays from the edges and FW-excited diffracted rays from the vertexes of the array) [1]-[3]. While the edge contribution is given by the uniform asymptotics in [1], the vertex contribution is given in [5], by means of a new appropriate transition function. The resulting array Green's function forms the basic building block for the full-wave analysis of planar weakly amplitude-tapered phased array antennas, and for the description of electromagnetic radiation and scattering from weakly amplitude-tapered rectangular periodic structures.

Free space rectangular array Green's function: time domain

Wide-band radiation by periodic arrays of sequentially pulse-excited antennas, or pulse-induced radiation by passive scatterers, suggest parameterization in terms of wave constituents in the time domain (TD). We have presented in a sequence of papers canonical dipole-excited TD Green's functions (GF) for infinite [14], [15] and truncated [6] periodic line arrays, and for infinite [7] and semi-infinite [16] periodic planar arrays. The radiated field has been expressed and parameterized in terms

of TD Floquet waves (FW). The resulting *scalar* TD GF has already been used advantageously to construct a fast TD method-of-moments (MoM) algorithm for wide-band analysis of infinite planar [8] and nonplanar [17] periodic structures. In [9] a TD network formulation is provided that may lead to computationally efficient representations of the vector electromagnetic field radiated by phased arrays. These TD transmission line concepts have already been used for non-phased arrays in a combined (TD-FW)-FDTD algorithm [18], to analyze periodic arrays of complex scatterers, such as Bow-tie antennas. The network formalism explored in [9], [18] is useful to define local TD current and voltage generators that excite TD transmission lines (TL). TD generators can be quantified by projecting data from numerical methods like the FDTD in [18] onto FW-mode vector eigenfunctions. The TD signals then propagate away from the generators along TD-TLs governed by analytical FW-matched algorithms. A similar concept has been used in [8], [17], to separate excitation and observation projection operations from the propagating part to obtain fast algorithms for evaluation of couplings between basis functions in a TD-MoM. Though TD-FW can be derived directly in the TD, asymptotic inversion from the FD yields the instantaneous frequencies which parameterize the constituent TD-FWs. The localization of the synthesizing wide-band frequency spectrum around instantaneous frequencies is due to the periodicity-induced dispersive FW behavior. The vector problem is addressed in [9], by resorting to a network formulation directly in the TD. A principal feature of the network-oriented approach is that E (TM) and H (TE)-type TD-FW modes can be separated and treated individually. The field is expressed in terms of TD transmission line Green's functions that obey standard network theory. Therefore, possible infinite planar vertically inhomogeneous media may readily be incorporated into the formalism.

Multilayer dielectric environment

The 3D semi-infinite AGF treatment in terms of truncated FW can be extended to an array of printed dipoles on a grounded dielectric slab. Rigorous saddle point asymptotics is used to derive the formulation in the *spectral* domain [11]. This leads to a hierarchy of edge-induced diffractions and couplings that are tied to slab-modulated propagating and evanescent FWs, and to slab guided surface waves (SW) and leaky waves (LW). To gain insight into alternative phenomenologies, the formulation is also derived in the *spatial* domain [12], which is parameterized via truncated Poisson summation, in terms of Kirchhoff-type representations extending over the semi-infinite radiating aperture, with corresponding diffracted rays emanating from the spatially fixed array edge along diffraction cones. The critical points in the uniform asymptotics for the *space domain* radiation integrals are the *end points* of, and the *saddle points* on, the integration interval, which give rise to edge-excited slab-modulated FW diffracted ray fields as well as to edge-excited slab-guided SW/LW contributions, and to truncated FWs that emanate from the truncated array aperture, respectively. In the *spectral* domain radiation integrals, the diffracted and truncated-FW phenomenologies are associated with saddle points and pole singularities, respectively, but their distinct GTD-type physical identification is far less apparent than in the *spatial* parameterization. With this approach, the variety of interesting interactions, which occur when two diffracted ray species

are phase-matched, can be highlighted [13] and physically interpreted.

Conclusion

During a period of almost 10 years of interaction with Professor Felsen, we have analyzed and validated the diffraction phenomena in both the frequency and time domains pertaining to large planar phased arrays of different topologies and environments and with quite general excitation profiles. The themes chosen here are the ones dearest to Professor Felsen among those treated with us. Although not shown by common publications directly coordinated in common publications, information and opinions on this topic have been fruitfully exchanged with the group at the ElectroScience Lab coordinated by Professor Pathak, who is presently working on the same subject [19]-[21]. Much more work had been planned with Professor Felsen before he died. We will try to sadly continue our research without him.

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