INNOVATIVE ELECTROMAGNETIC MODELING OF MULTIELEMENT QUASIOPTICAL FOCUSING SYSTEMS FOR MILLIMETER, SUB-MILLIMETER AND TERAHERTZ RANGES

DOPROG # 106E209

Project Information

State of the art

Today's leading edge in the R&D into electromagnetic wave systems, after successful development of the microwave range, is frequently associated with the millimeter (mm), sub-millimeter (sub-mm), and terahertz (THz) ranges. Here, the wavelength is a few mm and shorter that implies a wide use of optical and quasioptical effects and configurations for wave focusing, guidance, and directive radiation. E.g., beam waveguides formed by chains of metallic reflectors are attractive for a low-loss guiding in the heating of plasma in controlled nuclear fusion machines with the mm waves generated by high-power gyrotrons [M. K. Thumm, W. Kasparek, Passive high-power microwave components, *IEEE Trans. Plasma Science*, vol. 30, no 3, pp. 755-786, 2002], in the tomography of the same plasma with sub-mm waves, and in the feeding of mm-wave and far-infrared radio astronomy antennas [P.F. Goldsmith, *Quasioptical Systems: Gaussian Beam, Quasioptical Propagation and Applications*, NY, IEEE Press, 1998]. However, large electrical size (usually from 10λ to 100λ) makes the accurate simulation and engineering of such systems with popular today FDTD codes impossible. Besides of huge time of computations, they suffer of errors brought by the staircasing of scatterer boundaries and back-reflections from the virtual boundaries of computational windows [G. Hower *et al.*, *IEEE Trans Antennas Propagat.*, "Inaccuracies in numerical calculation of scattering near to natural frequencies", vol. 41, no 7, pp. 982-986, 1993]. At the same time, ray-tracing design methods like geometrical optics (GO) and physical optics (PO) or Gaussian beam propagation (GBP) [P.H. Pathak, *et al.*, "Novel Gaussian beam method for the rapid analysis of large reflector antennas", *IEEE Trans. Antennas Propagat*., vol. 49, no 6, pp. 880-893, 2001] are not uniformly accurate. Being very powerful tools, these methods still do not characterize fine wave effects in complete manner. This may lead to inefficient performance of geometrically designed multi-reflector systems [W.A. Imbriale, *et al.*, "Novel solutions to low-frequency problems with geometrically designed beam-waveguide systems", *IEEE Trans. Antennas Propagat*., vol. 46, no 12, pp. 1790-1796, 1998]. Therefore more complex and reliable computer-aided simulation tools are urgently needed, capable of making rapid analysis and even synthesis on moderate desktop computers. A general way to build more economic full-wave tools for the modeling of reflector or lens-type scatterers is to use integral-equation (IE) approach [D. Colton R. Kress, *Integral Equations Methods in Scattering Theory*, Wiley, NY, 1983].

Here, the crucial point is development of efficient discrete model, i.e. fast and convergent numerical algorithm having controlled accuracy. Although simple Method-of-Moments (MoM) with local basis functions gives satisfactory results for small reflectors, it fails if the scatterers are much larger than the wavelength λ. Today it is commonly believed that the domains of acceptable accuracy of GO/PO and MoM overlap on the 5-λ to 20-λ reflectors. Although reasonable for single reflectors, this is not so obvious for the multireflector and reflector-in-radome systems, especially in the sub-mm and THz ranges characterized with extended near zones. The recently developed "fast" algorithms [W.C. Chew, *et al.* (Eds.) *Fast and Efficient Algorithms in Computational Electromagnetics*, Artech House, 2001] are able to drastically shorten the computational time however their convergence is still not always guaranteed so far as they are used with the so-called first-kind IEs.

As a remedy, discrete models based on the Method of Analytical Regularization (MAR) or analytical preconditioning, i.e. conversion of a singular IE (SIE) for the surface current function to a Fredholm second kind matrix equation, were initiated in the 1990s [T. Oguzer, A. Altintas, A.I. Nosich, "Accurate simulation of reflector antennas by the complex source - dual series approach", *IEEE Trans. Antennas Propagat*., vol. 43, no 8, pp. 793-801, 1995]. Another efficient discrete model can be based on the Method of Discrete Singularities (MDS), which is a Nystrom-type interpolation method modified for the open scatterers with edges. Still the potentials of MAR and MDS in the accurate modeling of electrically large multireflector quasioptical electromagnetic systems have not been systematically demonstrated and exploited.

Problem statement

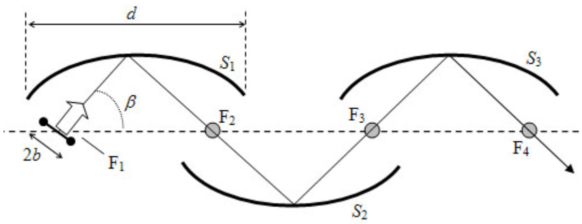

Figure. Sample geometry of generic multireflector beam waveguide formed by identical elliptic mirrors with coinciding focal points. The waveguide is fed by an aperture source, e.g., a horn. Similar beam waveguides are used for the plasma heating in nuclear fusion machines and for the feeding of large antennas at deep space communications facilities.

The subject of work is systematic computational experimentation towards the accurate analysis and optimal design of quasioptical multielement electromagnetic focusing systems such as open resonators, beam waveguides (see figure), and reflector and lens antennas. The techniques implied include modified versions of MAR and MDS, which have mathematically grounded convergence. Numerical study will be concentrated on the effects of multiple reflections and scattering between the scatterers having size up to 100λ, that is clearly prohibited for conventional MoM and FDTD schemes, on the focusing and directivity in such systems, and possibly on the influence of the imperfect conductivity.

Object and scope

The project objective is research into the computer-aided analysis and engineering of *multireflector open resonators, beam waveguide shaped as finite chains of reflectors, Cassegrain and the like antennas, elliptic focusers*, etc., used for the filtering, collimation, guidance and focusing of sub-mm and THz wave beams. This will be achieved by the mathematical and numerical study of the corresponding wave scattering problems as the *boundary-value problems for the set of Maxwell's equations with exact boundary, edge, and radiation conditions*. In the core is the use of singular boundary integral equations, which do not imply low or high-frequency approximations like GO and PO and lead to *convergent, stable, and efficient numerical algorithms*. Directivity of radiation, efficiency of focusing, wavelength dependences, and the field patterns in the near and far zones will result from this analysis, and the ways to improve these characteristics will be elaborated and analyzed.

Method (Please itemise the parameters to be studied and specify the method to be applied)

The methods of analysis and computer-aided simulation of multireflector open resonators, beam waveguides, and antennas will be based on rigorous boundary-type integral equations (IEs). This implies reducing each original boundary-value problem to a set of coupled IEs with corresponding edge and radiation conditions. The full-wave IEs are always of singular type. Therefore they should be either first converted to the Fredholm second-kind IE by using MAR and then discretized, or directly solved numerically with the aid of MDS. Both methods have been developed in Kharkov since the 1980s. The MAR has been also investigated in Bilkent and Izmir since the 1990s, with application to single reflector antennas. Each of the mentioned analytical-numerical methods has its specific merits and the both have guaranteed convergence and controlled accuracy – unlike FDTD, GBP, GO, and other approximations. On solving IEs, one obtains the surface currents, near and far field patterns, and can easily compute cumulative resonator, antenna, or beamguide characteristics such as Q-factor, directivity, sidelobe level, or transmission and focusing efficiency.

Results

Expected results

It is expected to quantify the effects of multiple reflections and scattering of non-GO field components in the multireflector quasioptical systems in the near and far zones, and effects of imperfect conductivity. For example, it will be possible to characterize the coupling between hyperbolic subreflector and parabolic main reflector in Cassegrain antennas and the beam guidance along finite chain of elliptic reflectors. Generally, the range of reflector size to the wavelength ratios to be studied will be some 10 λ to 100λ that implies that resonance phenomena and ray effects will exist together. Such analysis is a challenging task; however the methods like MAR and MDS are able to serve as reliable and efficient tools of modeling because of economic size of matrix discretizations.