Tailored two-dimensional finite-element formulations for ad-hoc analysis of waveguiding and mode-matching problems

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The analysis of homogeneous closed waveguides is known to be one of the first, if not the very first, problems to be addressed with the finite element method (P. Silvester, “Finite element solution of homogeneous waveguide problems”, *Alta Frequenza*, vol. 38, pp. 313–317, 1969) in the framework of computational electromagnetics. Since this two-dimensional scalar case, many developments have followed: extension to three-dimensional analysis, derivation of curl-conforming edge and higher-order elements, domain decomposition approaches, hybridization with other numerical or analytical methods, etc. This has led the finite element method to be considered one of the most well-established, reliable techniques to address cutting-edge problems in computational electromagnetics, with many reference books (G. Pelosi, R. Coccioli, S. Selleri, *Quick Finite Elements for Electromagnetic Waves*, Norwood, MA, USA: Artech House, 2009; J. Jin, *The Finite Element Method in Electromagnetics,* Hoboken, NJ, USA: Wiley, 2015).

Despite these long-known advancements, resorting to solving the afore-mentioned (and, at first glance, simple) problem of computing the modes in any waveguiding cross-section still plays a key role in computer-aided design methodologies that rely on the modal description of the fields, as is the case of the mode-matching method. In this case, not only an accurate calculation of these modal fields is required, but also the capability to compute as many modes (without skipping a single one) as necessary to ensure convergence. If the problem demands for it, it is also imperative to have a straightforward division into different classes or types of modes according to symmetries and possible excitations, as well as a proper identification of degenerate modes.

In this work, we will review some strategies and tailored two-dimensional finite-element formulations proposed by the authors to address some of the issues arising when analyzing waveguiding structures, especially focusing on obtaining proper modal decompositions of the fields to be used in further computer-aided design of waveguide devices through mode-matching techniques. Some of these strategies and formulations include the comparison of different types of meshes (structured quadrilateral vs. unstructured triangular) when the waveguide cross-sections have 90º corners, as well as the development of specific boundary conditions to model novel materials enclosing the waveguide (such as graphene) or to account for higher-order symmetries (such as rotational ones) in structures with a high number of degenerate modes. In the latter case, this is especially useful for devices conceived to operate with circular polarization.

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