# CAD OF WAVEGUIDE COMPONENTS FOR ANTENNA FEED SYSTEMS: STATE-OF-THE-ART

**Invited paper**

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***Abstract*** --- This papers summarizes the most recent research on CAD methods applied to waveguide components in antenna feed systems. General design strategies utilizing full wave analysis modules are outlined. Progress in CPU - efficient numerical codes and optimization methods is discussed. Advancement in full-wave design methods of individual waveguide components is summarized. Examples of high performance complete feed systems are shown.

## 1 INTRODUCTION

Modern communication and radar antennas employ highly sophisticated feed systems. The feed design quality continues to be critical to the antenna overall performance. At higher microwave frequencies (say, at the C-band and up) waveguide is a common transmission medium, mainly due to its low RF loss and high power handling capability. Over the recent decade a significant research effort was invested in advanced CAD methods for waveguide components and entire feed systems [1-3].

The research was focused on several design aspects. In the area of numerical modelling the emphasis was on improvement of full wave analysis tools in terms of accuracy and efficiency of handling complex electromagnetic problems. Another very vibrant area of research was in advanced optimization methods.

Novel design concepts leading to enhanced RF performance and/or simplified geometry have been also reported.

Tuning screws have been gradually eliminated from the feed components due to precision in performance predictions even for narrow-band components.

The use of low cost fabrication methods has been addressed through modelling of rounded corners resulting from a larger end-mill radius or the use of casting .

This focused research has resulted in dramatically reduced design time, improved RF performance, excellent modelling accuracy, reduced fabrication time and cost.

Within the limitation of allowable printing space this paper attempts to address the above mentioned research progress in the area of advanced CAD for antenna feed systems utilizing waveguide technology.

The paper is organized in three sections. Section 2 addresses general design strategies and guidelines. Section 3 focuses on advancements in EM – modelling methods and tools, whereas Section 4 summarizes state-of-the-art CAD of individual component in terms of design modelling efficiency and achievable RF performance.

## 2 GENERAL DESIGN STRATEGIES AND GUIDELINES

An efficient design strategy is crucial to a successful design of any component or subsystem. It is rather challenging to arrive at an universal method for each single component but it is quite possible to specify a general design approach that is then modified to suit specific design goals of individual components.

A typical design process of an antenna feed component (or subsystem) can be broken down into the following steps:

**Specification of the design goal**. which includes RF performance specifications with margins for manufacturing tolerances, thermal shift and performance degradation over system's life ;

**Formulation of the design constraints;** for example, weight, volume, minimum size of a geometrical detail or a geometrical parameter which often is related to the power handling capability, structural strength, manufacturabilty; this also includes budget and schedule issues.

**Trade-off Analysis** which includes criteria determined from the first two steps. This step leads to the baseline design selection;

**Preliminary design**. If available, an existing data base can be used to determine initial electrical dimensions of the component. Frequency scaling is a common practice, especially for wide-band components. Many waveguide filter types can now be synthesized using full-wave characterization of coupling sections. Transformers and directional couplers can be also synthesized using transmission line theory.

**Full wave analysis**. A variety of powerful numerical methods utilizing full wave characterization of arbitrarily shaped waveguide discontinuities or entire components have been recently developed. These methods allow the computation of the component's S-parameters over a predetermined frequency range in a very efficient manner.

**Power handling capability verification.** In antenna feed systems average power handling requirements are rarely a concern since the power dissipated in low-RF-loss waveguides is typically very small. The peak power requirements are related to either plasma breakdown (corona) or electron breakdown in vacuum. For space equipment, peak power requirements are verified by computing maximum voltages across small gaps resulting from selected design concept and comparing them against experimentally determined threshold.

**Optimization.** The preliminary design rarely leads to the component's RF performance meeting all design requirements. Therefore, an optimization process must be employed to arrive at the required design goal. A number of advanced optimization strategies have been recently developed. For many components an iterative full-wave analysis process coupled to some gradient or non-gradient design objective function verification / feedback algorithm can be used. For some more complex components or systems with very large number of variables, other methods such as space mapping might be more suitable. Many of commercially available full wave design software are equipped with optimization tools.

**Dimensional Sensitivity Analysis -** Once the nominal components dimensions have been established manufacturing tolerances should be considered to avoid excessive manufacturing cost without compromising the RF performance. This design step is especially critical for components operating above the 20 GHz frequency range where manufacturing tolerances are typically very tight.

**Experimental Design Verification -** The accuracy of the above outlined CAD procedure should be verified by direct measurement. In recent design practice, the stage involving manufacturing and testing breadboard models is often skipped. However, such an approach is justified mainly for hardware with design heritage. Novel components are typically developed involving breadboards. The typical risk areas are in spurious modes spikes appearing in the frequency response, insufficient convergence used in the full-wave based design process, frequency shift due to the limited numerical accuracy of the software, imperfections in the geometry and others. Some "soft" tuning typically is a solution to potential discrepancies. If tuning is prohibited due to, say power handling issues, another design iteration is sometimes necessary.

## 3 CAD METHODS AND TOOLS

Accurate performance predictions of state-of-the-art waveguide equipment require modelling capabilities based on electromagnetic (EM) field theory. A large variety of EM codes is commercially available, e.g. [4]. Without going into the individual details of such codes, the design engineer often finds two disadvantages associated with them. First, relatively few are equipped with optimization tools to design or numerically fine-tune a circuit or component. Secondly, many have field solver capabilities which are more desirable for general-purpose applications rather than waveguide structures. Although field solvers have experienced a significant speed-up process over the last years, they are likely to be outperformed by modal field-matching approaches if the geometry fits the coordinates of the modal bases used. Therefore, in CAD methods for waveguide technology, general field solvers are predominantly used to verify a design, not to design a component. Essentially, the CAD consist of three blocks:

**Targeted Software**: This is the center piece in waveguide CAD tools. It consists of software packages which are geared towards a specific component or class of components. Many routines are based on modal field-matching techniques and cover a variety of rectangular and/or circular waveguide components such as filters, multiplexers, transformers and junctions, polarizers and orthomode transducers – to name only a few. They provide an accurate analysis within a reasonable CPU time and can easily be linked to synthesis and optimization tools. Recently, companies such as MiCIAN combined a variety of different waveguide structures and methods in commercially available CAD packages [5].

**Initial Design**: This is probably the most important step in modern CAD. A large class of mostly rectangular waveguide discontinuities and components have been characterized in terms of equivalent circuits, e.g. [6], which allow a synthesis of required VSWR's or coupling coefficients. Many of these design strategies have meanwhile been coupled with targeted software codes and hence allow a quasi-synthesis of a large variety of waveguide components. They also work well in circular or elliptical waveguide structures, although with reduced accuracy. Hence, they are capable of providing excellent initial design dimensions to be fine-tuned by optimization routines. Recently, and especially for high-performance filter structures, is was found that optimizing the (equivalent-circuit) coupling matrix of a filter structure has many advantages over traditional designs by coupling-matrix rotations [7].

**Optimization**: Linked to an accurate analysis tool, optimization varies a number of design dimensions to fit the performance specifications of the component. Whereas much effort is still spent on enhancing individual optimization strategies, it is widely accepted that as long as the initial design values are good and the cost function is well-behaved, the majority of optimization codes will arrive at a satisfactory solution to the design problem. Among the many different optimization approaches, e.g. [7], the MiniMax algorithm [9] has turned out to be a very reliable tool.

In the event that good initial values are not available, optimization runs with fast and reliable targeted software packages will not necessarily converge within a reasonable design time frame. This is mainly due to the significantly increased number of optimization steps. The only option is to reduce the time required for a single optimization step by replacing the accurate targeted software with an inaccurate, but significantly faster equivalent-circuit model. Optimization is now carried out with the equivalent-circuit model, but the model itself is frequently modified and updated by the accurate targeted software. This approach has recently been introduced as space mapping.

## 4 PERFORMANCE AND CAD STATUS

**Waveguide runs** To accommodate the variety of microwave system applications and their particular antenna and feed system designs there are four common waveguide types, namely, the common rectangular, circular, ridged, and elliptical waveguides. Up to now, most standard CAD methods (mode-matching, FEM) allow the computation of bends [5] and twists [10] in the rectangular waveguide even with uncertainties as milling radii, to be considered in integrated structures. Ridged waveguides are used for extreme broad band applications, although their handling is substantially more expensive compared with rectangular types. FEM or FDTD based CAD tools are available to solve low VSWR ridge waveguide routing issues. Elliptical waveguides (smooth wall and corrugated) were introduced for very long, low loss interconnections between transceiver and antenna. Their substantial advantage over other types is the realization of long, high performance, continuous waveguide runs. Recently an exact solution of the complex corrugated type has been obtained by a full wave analysis [11]. These results have been used to establish overmoded operation for waveguide runs with further improved insertion loss properties at millimeter waveguide frequencies [12].

**Filters.** Owing to the substantial differences of the crucial requirements (insertion loss, rejection, power handling, size, costs) for the variety of applications, there is a broad spectrum of filter designs. Hence, there are numerous papers concerning CAD of filters and, thus, only few examples are presented due to the lack of space. Broad band filters such as high pass filters using waveguide sections below cut-off, corrugated and waffle-iron low pass filters can be designed accurately by CAD [5] with commonly no need of any post tuning. Broad band cavity filters with cross couplings for the realization of tailored filter responses may also be designed without the need of tuning in integrated waveguide structures [13].

Narrow band channel filters are basically realized by overmoded rectangular cavity structures or use circular dual-(multi-) mode cavities. Available CAD tools provide accurate prediction of response and geometry of complex cross coupled structures [14] as well as of multimode cavity configurations [15,16]. However, fine tuning is usually necessary since the tolerances of state-of-the-art manufacturing methods usually exceed the allowable deviation of the dimensions. It should be noted that the application of CAD yields a tremendous reduction of experimental design expense.

**Diplexers.** Diplexers in antenna feed systems typically require either narrowband (for single channel separation) or broad-band operation (e.g. in multi-channel satellite antennas). Typical requirements include low passband insertion loss high power handling capability, and high isolation between channels. These tight performance specifications can be currently met with designs without any tuning elements over a wide frequency range including Ka-band (30/20 GHz). The common filter types are: waveguide stubs, inductive irises, high-pass waveguide sections or corrugated low-pass filters. The filters are combined either by T-junctions or bifurcations [17]. Mode matching techniques are commonly used in full wave modelling. Initial design encompasses full-wave filter synthesis and adjustment of the virtual short circuit plane positions. MiniMax-type optimization routines are very efficient optimization tools. Such fully supported CAD design of these components is generally necessary to accommodate extreme requirements that are sometimes imposed on these components. For example, several Ku-band diplexers have been designed for satellite antenna systems (NAHUEL, SINOSAT, ASTRA2B) satisfying low insertion loss (<0.15 dB), high return loss (>26dB) and band isolation (>50dB), high power handling capability (>500W CW, >12kW peak power handling, passive intermodulation product control >200dBc) versus a space environmental temperature range of -100 to +140 °C.

**Multiplexers.** The different multiplexing principles are summarized in [18]. Owing to the modularity of the circulator/filter chain and directional filter approaches, the advances in CAD are dedicated to the required components (see filter and coupler). Due to the large complexity of multiple channel manifold multiplexers the principal design approach in [18] using full wave modelling in the common manifold region and equivalent circuits for the narrow band filters is still suitable. Recent advancements have been provided in [19] for the determination of initial manifold distances to improve the start conditions reducing the number of required optimization steps and thus overall computation time. However, in a final step the obtained equivalent circuits of the filters are mapped to the geometrical dimensions [16] yielding a substantial reduction of experimental expense.

**Orhomode Transducers** A good survey of the different basic OMT – types is given in [18]. The proposed CAD possibilities have been extended due to the recent progress in analysis and optimization [20] methods allowing also design support of OMTs with a common circular waveguide. The need of full wave designs has been shown lately for mm-wave applications [21] since experimental adjustment of such diminutive structures is nearly impossible. (However, it should be noted, that these designs comply with essentially reduced performance demands.) Due to complexity of high performance ( wideband) OMT the design of a compact device is still a challenging engineering task. For example, the sophisticated compact design in [22] for large scale low cost production can (up to now) hardly be designed by available CAD tools.

**Polarizers.** CAD tools have been developed over the past decade to design polarizer structures in a number of different waveguide technologies. Efficient modal field-matching software has long been available for rectangular corrugated polarizers, e.g. [1]. More recent codes include circular waveguide ridge and pin polarizers [23], and combinations of circular and rectangular sections, e.g. [24], which are also suitable for dual-band applications. For critical cases, cost functions in the optimization process include specific angle specifications between the two linear components (usually $\pm 90^{o}$) to counteract the influence of connected circuitry.

Septum polarizers assign two different linear polarized ports to left-hand and right-hand circular polarized waves in the common port. CAD advances have been reported on the variable septum thickness [25] and the circular septum polarizer [23] in which a bow-tie shaped septum approximation is used for an efficient design procedure.

**Transformers, Transitions**. Transformers and transitions are very common in antenna feed systems due to the need for combining components with RF ports of different cross-sections. Design of transitions in common Tx/Rx antennas is typically more challenging, especially if the Tx and Rx channels are widely separated in frequency. The design of these transitions aims at high performance and large scale, low cost production, since these transitions are often required in relatively large quantities for single polarized antenna feeds (rectangular-to-circular) and for the elliptical feeder waveguides. Thus, a novel BCMM CAD has been established for the computation of arbitrarily curved cross sections of transformer steps within a desired transition [12]. The proper consideration of milling radii at the rectangular port within the CAD allows the realization in one part by state-of-the-art CNC milling from the flange faces facilitating manufacturing and costs.

**Power combiners/dividers.** The progress of full wave CAD tools also extends and facilitates the design of couplers / hybrids. In [26] a Riblet hybrid design variant is introduced that accommodates fully CAD and manufacturing demands, however, with penalty of reduced bandwidth. Recently, a new hybrid type has been established that is based on a common overmoded waveguide supporting three propagating modes ($TE_{10}$, $TE_{11}$, and $TM_{11}$)[27]. This design needs in particular full wave CAD support to accommodate with optimal performance demands. The inclusion of milling radii by advanced CAD tools [5] allows to avoid experimental fine adjustment.

**Entire feed systems** In addition to the most common single or dual polarized antenna operation, there are often extra tasks imposed on the feed system design. A brief outline of some examples is given below.

Applications with integrated transceiver/antenna solutions must provide receive/transmit signal diplexing, suppression of spurious signals like harmonics and broad band matching properties while optimally fitting into a dedicated area in a housing with direct interconnection of the antenna port with the LNA and transmit amplifier port. Moreover, compatibility of electrical and mechanical design has to be considered for applications utilizing different frequency bands. An integrated feed system concept satisfying these demands consisting of dielectric back scatter feed, rectangular-to-circular waveguide transition, harmonic reject filter, diplexer and isolators is shown in Fig 1.

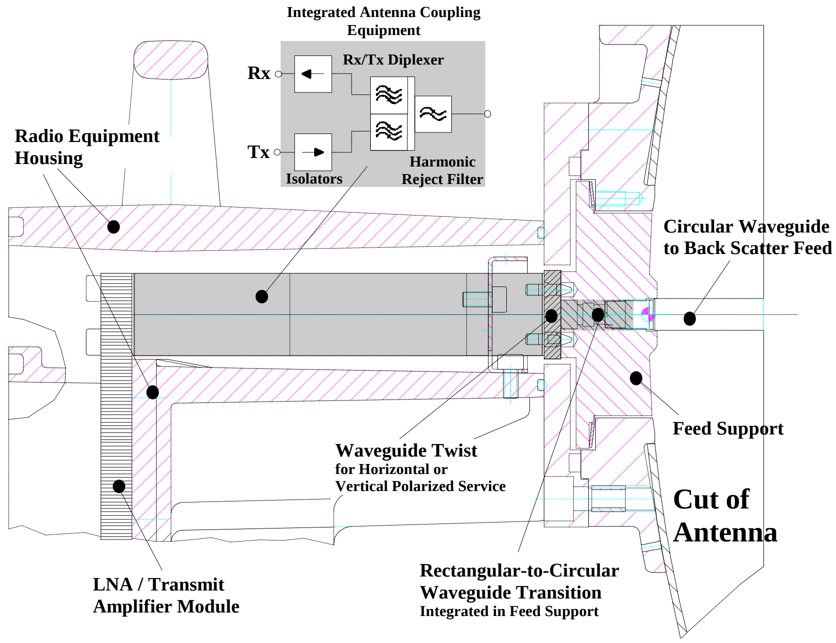

Figure 1. Antenna feed system for a short haul radio featuring an integrated antenna/transceiver solution (Marconi)

The design challenge for feeds employed in modern communication satellite antennas is predominantly in stringent requirements for low RF loss, power handling, polarization isolation and low PIM level. Fig 2 shows a 30/20 GHz feed system used on the Koreasat-3 Ka-band Gregorian antenna, [29] designed by EMS Technologies, Canada. This high performance feed system includes a corrugated horn, a dual band polarizer, a diplexer and waveguide runs. Excellent RF performance has been achieved without any tuning.

For high accuracy tracking (Monopulse) or for increase of transmission reliability (angle diversity) feed systems are used that provide independent access to the signals of extra antenna beams. In the Monopulse case only a narrow band beacon signal has to be detected while for angle diversity a complete frequency band must be served [30]. Fig 3 shows the block diagram and photograph of a 6 GHz angle diversity feed system that is based on higher order mode excitations in the feed. It consists of the feed horn, a multiple mode transition, two OMTs and two Magic Tees, each connected symmetrically to the vertical and horizontal polarization port of the OMTs, respectively. Thus, the interface ports at the Magic Tee provide access to a main and a diversity ('Monopulse') beam, respectively. In detail, a signal at the sum port of the Magic Tee dedicated to the vertical polarization excites the $TE_{10}$ mode at the multiple mode transition that is associated with the vertical polarized main beam. A signal at the differential port excites the $TE_{11}/TM_{11}$ modes assigned to the horizontal difference beam. The same holds for the Magic Tee serving the horizontal polarization with the modes $TE_{01}$ and $TE_{02}$ dedicated to main and difference beam of the antenna, respectively.

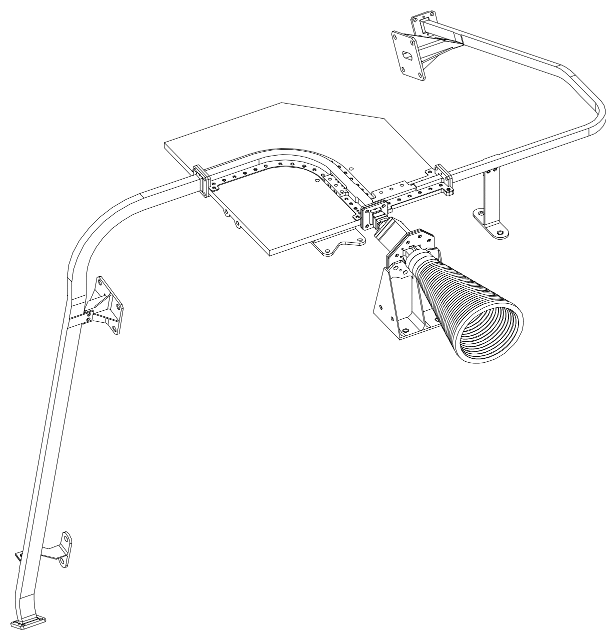
Figure 2. Koreasat-3 Ka-band antenna feed.

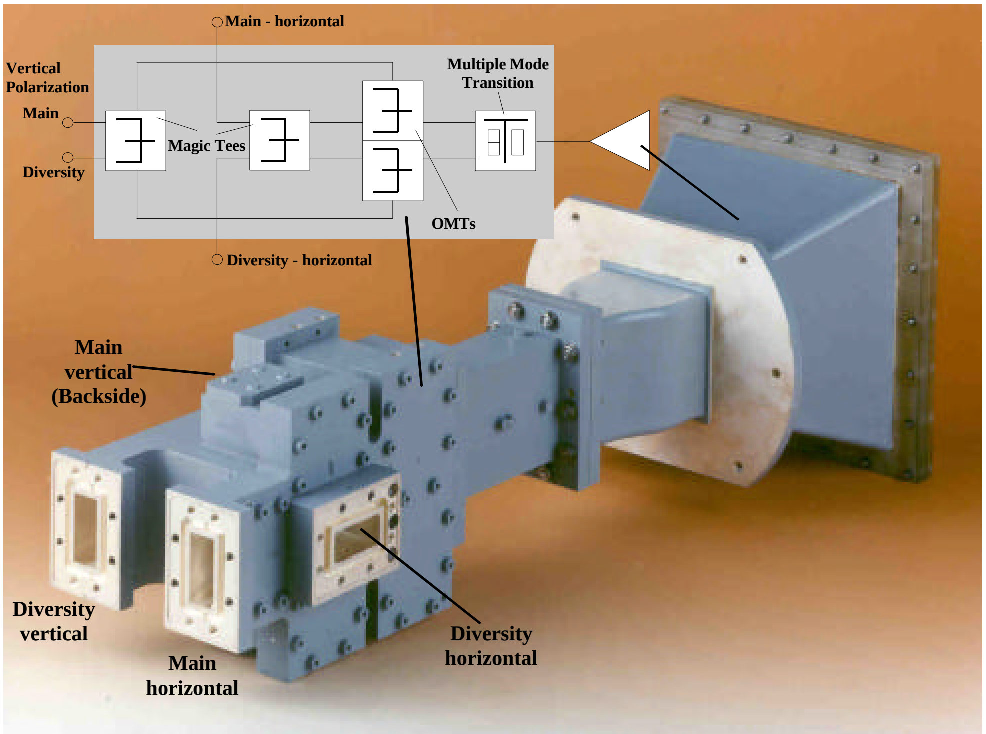


Figure 3. 6GHz dual polarized integrated angle diversity feed system, based on multiple mode excitation for the generation of independent horizontal and vertical main and diversity beams (Marconi)

## 5 CONCLUSIONS

This paper has demonstrated that the currently available CAD tools are capable of providing designs of complex waveguide antenna feed systems at dramatically reduced cost. This is the result of elimination of tuning elements and capability in modelling features of low-cost fabrication methods. The design time has been significantly accelerated due to the use of ever improving full wave EM modelling tools and efficient optimization strategies.

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