WAVEGUIDE-FED SLOT ANTENNAS AND ARRAYS: A REVIEW

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ABSTRACT

Conceived in the forties, slot array antennas have reached a state of maturity. However, there are still many problems addressed in the current literature. This paper presents an overview of the significant publications on waveguide-fed slot antennas and arrays.

1. EARLY WORK

The use of slots cut in rectangular waveguides as radiating elements had its beginning during World War II in Canada due to the pioneering work of Watson, Stevenson, and Booker. Stevenson [1] gave a sound theoretical basis to the experimental work of Watson [2] by formulating an integral equation for the slot aperture electric field. The integral equation was solved for resonant-length slots using the waveguide Green's functions and the concept of equivalence of slots and dipoles derived by Booker [3] based on Babinet's principle. Subsequently Oliner [4] developed a variational solution to the slot aperture electric field and deduced the slot characteristics away from the resonant frequency. Oliner's formulation did not take into account the dependence of the resonant length of the slot on

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its position and orientation in the waveguide wall. Yee [5] extended Oliner's variational procedure and obtained the resonant length of a longitudinal broadwall slot as a function of the slot offset from the centerline.

The slot antenna became popular since the feed and the radiating structure were integrated in the same waveguide. Also, the insertion loss of such a system is very small. Since the excitation of a radiating slot could be controlled precisely by its physical parameters, an array of slots cut in a waveguide wall could be designed to have the desired radiation pattern. Stegen [6] obtained a set of carefully measured data and facilitated the design of slot arrays by producing universal curves for the conductance and susceptance of longitudinal slots cut in the broadwall of a rectangular waveguide as a function of slot length normalized to its resonant length. Stegen's data served as a standard for a long time until the development of accurate computer codes became possible in recent times.

2. ARRAY DESIGN AND SLOT MODELS

The method of designing slot arrays evolved since the fifties and eventually an accurate procedure for longitudinal broadwall slots was introduced by Elliott and Kurtz [7] for resonant or standing-wave-type arrays. A resonant array is characterized by a short circuit termination and a half guide wavelength spacing between slots. In that procedure, external mutual coupling between slots was taken into account based on an analogy to dipoles. The design procedure was improved with the assumption of a half-cosine equi-phase aperture distribution that is also valid for slots cut in dielectric filled waveguides [8]. Reciprocity consideration was invoked to determine mutual coupling expressions. The design of traveling wave arrays where the slot spacing is chosen for producing a squinted beam follows the procedure given in [9]. The input data for the above-mentioned design procedures are the self-admittance and the resonant length of slots as a function of offset and length. During the sixties and seventies such data were obtained experimentally. A design procedure using network models for the array and feed has been described by Mazzarella and Panariello [10].

Because of the cost and complexity of the experimental measurement of slot data, there was a need to characterize slots accurately by a computational process. This led to the investigation of the moment method

solution of the pertinent integral equation for the slot aperture electric field. Khac and Carson used the moment method technique to study the longitudinal slot [11-14]. While their computed values of slot conductance were found to be accurate, the accuracy of computing the resonant length was not adequate due to the use of pulse expansion functions. Pulse functions produce a discontinuous aperture distribution with non-zero values at the slot edges. Further efforts that are reported include a global sinusoidal Galerkin technique [15, 16]. This method has the advantage that the first expansion term is a very good approximation to the aperture distribution of a resonant slot. Therefore, as few as three terms are adequate for a good solution in many cases. Also, since the expansion functions are smooth and approach zero at the ends they yield good accuracy for the resonant length. However, in order to obtain better than 0.5% accuracy for the resonant length, one may need about nine expansion functions. Sangster and McCormick [17] demonstrated the use of a design process employing theoretically calculated slot data.

Stern and Elliott's investigation [18] yielded several interesting results. They showed that the global sinusoidal Galerkin and piece-wise sinusoidal Galerkin models were in excellent agreement. Their results for the zero-thickness case agreed very well with experimentally measured data for very thin wall slots. For small values of the waveguide 'b' dimension and for large values of slot offset from the centerline, they found that the shunt model was poor. This is due to the fact that the aperture field has a substantial odd-symmetric term with respect to the center. Since modern slot arrays employ reduced height waveguides the previous design procedure has a limitation for such arrays. Therefore Gulick and Elliott proposed a new design procedure [19]. The procedure involved an iterative solution of the coupled integral equations of the entire array using the moment method. This solution has been considered to be limited to small arrays because of the computational burden.

2.1 Various Radiating Elements

Moment method solutions of the pertinent integral equations for various slots have been studied because of their applications in arrays. The broadwall compound slot, offset from the centerline and tilted with respect to the waveguide axis, exhibits the interesting property that its amplitude and phase can be independently controlled by offset and tilt, still keeping the slot resonant [20]. Compound slots are ideally suited to traveling wave applications such as fuze antennas of missiles, where one wants to produce

a beam at an angle with respect to the axis of the missile. In resonant arrays there is a limitation to the amount of phase control. A theoretical investigation of the compound slot has made it possible to understand its properties [21, 22]. The singular part of the Green's functions required special treatment in that analysis. The source region singularity, responsible for the TM_{∞} mode contribution in the moment method analysis, has been noted previously [13]. For narrow slots the edge condition is found to be not significant and an assumption of a uniform transverse distribution yields very accurate results. The wall thickness effect may be taken into account rigorously by treating the thick aperture as a cavity [21] or as a stub waveguide [16]. The centered inclined radiating slot is another useful antenna element that behaves as an excellent series element [23]. Numerical difficulties encountered in the study of the transverse slot with the use of pulse expansion and point matching procedure have been circumvented by a choice of edge based expansion functions [24].

Josefsson [25] has presented a solution to the transverse slot radiating into a half-space region or into a region of parallel plates. The use of baffles in the exterior region allows one to have a slot spacing of one guide wavelength and suppress the grating lobes. One major problem of this radiating element is that there is not enough control of excitation amplitude, and hence, the input impedance of such an array is very high, resulting in a matching problem. Recently Dich and Rengarajan [26] analyzed the transverse slot radiating into a finite-length parallel plate region opening into a half-space. The effects of finite width parallel plates are illustrated by the experimental results provided in that work. The problem of the longitudinal slot cut in the broadwall of a dielectric-filled rectangular waveguide is addressed in [27]. Joubert and McNamara investigated the dyadic Green's functions for a partly dielectric-loaded rectangular waveguide [28] and have analyzed the longitudinal slot cut in such a waveguide [29]. The transverse slot cut in a partly dielectric-loaded waveguide provides greater control of excitation and it is possible to have less than one free-space wavelength spacing between slots, still keeping the slot spacing equal to one guide-wavelength [30].

Rexberg [31] and Katehi [32] have determined the properties of a longitudinal slot with a dielectric cover. This subject had previously been studied by Bailey [33, 34]. Falk [35, 36] presented the solution to the longitudinal slot cut in the broad wall of a single ridge waveguide. A moment method solution of the problem of a longitudinal slot radiating

between infinite parallel plate waveguides was presented by Forooghi [37]. The problem of finite-length parallel plate waveguides has been solved in terms of a spectrum of two-dimensional solutions using the Fourier transform technique [38, 39]. In a further development [40] the spectral domain technique has been applied to a longitudinal slot radiating into an arbitrary cylindrical outer structure. The use of baffles reduces the off-axis lobes (butterfly lobes) produced by alternating slot offsets in a conventional slot array, first analyzed by Gruenberg [41] and later studied by Kurtz and Yee [42]. Baffle-like structures are also used in some dual-polarized slot arrays [43]. Centered longitudinal slots excited by means of posts [44] or irises eliminate Gruenberg lobes. The use of probes was discussed first by Clapp [45]. Iris-excited slots have been addressed in [46-48]. It has been found that a centered longitudinal slot excited by a compound iris exhibits broader bandwidth than an offset slot since the resonant characteristics of the slot and the compound iris are complementary [46, 48]. Parallel plate radial line slotted arrays were investigated by Kelly and Goebels [49, 50]. Later similar antennas were studied extensively by Ando and others, e.g., [51]. A waveguide-fed parallel plate array antenna has been investigated by Hirokawa et al. [52].

The narrow wall tilted slot usually extends to a small region on both broadwalls. The complexity of the exterior region for this problem makes it very difficult to analyze. Compact resonant structures that do not extend into the broad wall, such as I- or C-shaped elements, have been investigated in the past [53-55]. The narrow-wall slot has been analyzed by employing approximate exterior Green's functions by Pan et al. [56, 57]. Numerical techniques such as the finite-difference time domain technique and the finite element technique may be employed to obtain slot data necessary for design or analysis [58, 59]. An array of tilted narrow wall slots gives rise to cross polarization in the off-axis planes. Ajioka proposed a solution to avoid the cross polarization problem by keeping the slots untilted. In order to excite the slots, two wires were used inside the waveguide for each slot. This problem, as well as a variation involving etched strips in a dielectric instead of wires, have been studied recently [60-62]. Dudley [63] investigated iris excited narrow wall slots.

2.2 Extension/Variation of the Design Procedure

The design of an array of centered-inclined broadwall slots, by modeling them as series impedances in a transmission line, is discussed in [64]. The mutual coupling effects were found to be less in that case than those for

longitudinal slots. Kim and Elliott [65] studied the problem of a longitudinal slot array fed by single-ridge waveguide. Hamadallah [66] modified Elliott's design equations to allow the analysis of a slot array. These equations may be used to study the performance of an array at various frequencies in the desired band. A variation of a traveling wave array with a center feed has one half of the array in the 'forward-fire' mode and the other half in the 'backward-fire' mode. The two halves produce beams pointing in the same direction. Such a pattern is found to be more stable as a function of frequency as compared to a typical end-fed traveling wave array [67-69]. The design of a planar array as an extension of the procedure for linear arrays is presented by Elliott [70]. The concept of incremental conductance, first introduced by Watson [2], may be used to design any reasonably large slot array by following the procedure given in [70]. Yee [71] has compared the mutual coupling effects for an infinite array and that for a finite array and found the infinite array model to be a good starting approximation in many cases. Derneryd and Petersson [72] studied the overloading effects of the radiating slots on bandwidth. Overloading was found to improve the impedance bandwidth whereas it reduces the bandwidth for the radiation pattern performance. Therefore, an optimum normalized total active admittance of about two for each radiating waveguide is recommended. The design of a shaped beam pattern produced by a planar array of longitudinal slots with compound coupling slots has been presented [73]. As the number of elements in an array gets larger the bandwidth becomes lower due to the resonant nature of the array. In order to realize greater bandwidth, the array is broken into sub-arrays. Watson and Ringer [74] discuss some practical considerations in the design of feeding networks.

2.3 Analysis and Computation of External Mutual Coupling

Mutual coupling requires most of the computation time in the analysis or synthesis of slot arrays. Therefore, the analysis and computation of mutual coupling has received much attention in the literature since the early fifties [75]. The dipole analogy to slots has been exploited in the computation by Hansen and Brunner [76]. A Taylor series approximation around half wavelength slots is employed by Mazzarella and Panariello [77]. The geometrical theory of diffraction has been used to include the edge effects of a finite ground plane [78, 79]. Series expressions have also been investigated [80]. The mutual coupling between conventional and compound slots is studied in [81] wherein the computation of the mutual coupling expression for narrow slots has been reduced to a single integral.

Pan et al. [82] have presented results for mutual coupling between side-wall slots. Their method is approximate since the mutual interaction between corners is not accounted for. Rengarajan [83] has investigated the mutual coupling between longitudinal broadwall slots radiating between baffles. A similar analysis for transverse slots has been published recently [84]. Mutual coupling between slots radiating into different exterior cylindrical structures has been investigated by different formulations such as the electric field integral equation (EFIE) and the magnetic field integral equation (MFIE) for the axial fields and MFIE for the tangential components [85].

A planar array employed in mono-pulse applications produces three simultaneous beams, one sum pattern and two difference patterns. Since the same aperture is used for all three beams with different feed networks, each slot experiences different mutual coupling effects for each of the three beams. Strictly, the design procedure will yield three different values of offset and length for the three beams. Clearly, it is not possible to realize the slots in a single aperture. Schaffner et al. [86] provide an optimum compromise by averaging the three values of offsets and lengths one gets for each slot. The same problem exists for waveguide slotted arrays with electronically scanned beams. Derneryd provides a good compromise for the aperture distribution of mono-pulse patterns [87].

2.4 Coupling Slots

Planar slot arrays generally consist of a main waveguide and a family of orthogonal branch waveguides containing radiating slots. In the case of longitudinal broadwall slot arrays, coupling slots cut in the common broadwall feed desired amounts of power into each branch waveguide. Elliott and Kurtz [88] developed the key relations for the four-port couplers. Integral equation/moment method solutions indicate that the centered-inclined coupling slot possesses desirable characteristics [89] whereas longitudinal/transverse coupling slots may have some problems [90]. The compound coupling slots have the property that generally it is possible to realize any amplitude and phase for coupling, still keeping the slots resonant [91]. For narrow wall slot arrays a coupling slot configuration has been proposed by Hilburn et al. [92]. Broadwall slot coupling into butt-ended waveguides, analyzed by Rengarajan and Elliott [93] may have applications as experimental fixtures or feeds. Centered-inclined coupling slots have also been analyzed by Hanyang and Wei [94].

2.5 Weakly Excited Slots, Wide Slots and Round-Ended Slots

When the number of radiating or coupling slots becomes large in a waveguide, the amount of coupling from each slot becomes small. A weakly excited broadwall slot is characterized by a small amount of offset and/or tilt. In that case the conventional assumptions employed in the analysis such as ignoring E-longitudinal and the use of even transverse distribution for the E-transverse are inadequate. Therefore, the conventional moment method model becomes poor and it fails completely for a centered longitudinal slot. Rengarajan and Derneryd [95] proposed an improved scattering model that corrects the moment method data with experimental data for centered slots. Peterson and Rengarajan [96] have given a rigorous solution of the weak slot problem by solving for both components of the slot aperture electric field. The complete aperture distribution is obtained in terms of global polynomial basis functions, Jacobi and Legendre functions with appropriate edge conditions. They have shown that the E-longitudinal has a significant contribution to the scattered field. A simple prescription for the weak slot problem in terms of parasitic effects at the slot edges has been proposed by Albertsen [97].

Sangster and McCormick [98] have investigated the wide slot problem without any special consideration to the longitudinal component of the E-field. Lodone [99] has shown that the longitudinal component of the electric field is significant for slots with a length to width ratio less than seven. Peterson-Espino et al. [100] have demonstrated excellent agreement between results computed by the rigorous model [96] and experimental results for very wide slots. The analysis of a slot generally assumes a square end because of the mathematical convenience whereas slots made by a milling process have semi-circular ends. Theoretical treatment of round-ended slots has not been successful so far [101]. Previous work has shown that equivalence between round-ended slots and square-ended slots based on an 'equal area criterion' is generally a satisfactory engineering solution [16, 95].

3. ADVANCEMENTS IN THE ANALYSIS

Demanding performance requirements of modern array antennas have given rise to advancements in the analyses of slot arrays. Elliott and O'Loughlin [102] found that the TE_{20} mode coupling between adjacent radiating longitudinal slots was significant when the slots were close to the

centerline. When three different waveguide heights were studied for the same antenna, the smallest offsets occurred for quarter-height guides in their study. Later studies [103, 104] showed that the TE_{20} coupling was the most significant of the higher-order modes and that it is significant for small values of offsets and tilts. In the case of a junction involving a coupling slot and a pair of straddling radiating slots, higher-order mode coupling effects are found to be significant. Analysis of such a junction problem is facilitated by the Green's functions with a spectral integral representation as presented by Mahon [105], since the source region and field regions are easily separable even for a tilted slot. Rengarajan and Shaw [106] have solved the junction problem, with the use of Mahon's Green's functions when a singularity was encountered in the coupling problem. Seki's virtual cavity technique [107, 108] obviates the need to work with the singularity in the Green's function by a different formulation. It has been successfully employed in [61, 62]. Senior [109] has presented results for the higher-order mode coupling effects for the shunt-series coupling junction. Higher-order mode coupling effects are less serious for this junction compared to the conventional junctions employing centered-inclined coupling slots.

Petersson et al. [110, 111] have presented the results of the ERS-1 slot array antenna design and performance analysis. Design of slot arrays pose challenges when severe mutual coupling effects are present. One needs to investigate alternate slot excitations producing the same given power pattern. In some cases it is possible to realize a beam with a small squint that is compensated for mechanically. The multiport approach to design a planar array of narrow wall slots, implemented in the Canadian Radarsat antenna, is described by Wood [112]. The radar cross-section (RCS) of the slot array has not received much attention in the literature. Josefsson [113] has studied the problem of scattering from a single slot. Fan and Jin [114, 115] have presented analytical results for the RCS of cylindrical and planar slot arrays in terms of two contributions, structural scattering and slot scattering. Sangster et al. [116, 117] have discussed waveguide-fed dual polarization systems. Dual polarization slot antennas are also realized by stacking waveguides with alternating vertical and horizontal polarization. Longitudinal and transverse broadwall slots and narrow wall slots have been employed in such applications [43]. Ando and Hirokawa have given an excellent overview of radial line and conventional parallel plate fed slot arrays for direct broadcast satellite and millimeter wave applications [51].

4. MANUFACTURING TECHNIQUES

Standard numerically controlled metal machining and metal joining processes such as dip-brazing, soldering, and electron beam welding have successfully been used in the manufacturing of waveguide slotted array antennas. However, high precision is required due to narrow tolerances for advanced applications. Laser cutting and laser welding have also been used, especially with small values of wall thickness. Planar slotted arrays for the 60 GHz band have been realized using photo-lithography techniques [118]. An overview of manufacturing methods is presented by Sikora and Womack [119]. Where light-weight and thermally stable structures are desired metallized composite materials have found use [120, 121].

5. SLOT ARRAY ANTENNA SYSTEMS

Waveguide slot array antennas have found wide-spread use, both for communication antennas and for radar applications. For lack of space only a few significant examples are referenced here. An advanced flat plate array with several sub-apertures has been described by Cross et al. [122]. A 10-meter long fixed beam C-band array is used in a space-borne SAR application (ERS-1) [110]. The waveguide slot array is ideally suited for one-dimensional electronic scanning. An early implementation using frequency scan is found in the AN/SPS-48 radar and similar ones described in [123]. Electronic scanning of slotted waveguide arrays by means of electronic phase shifters is employed in the well-known AWACS airborne radar [124] and the Firefinder AN/TPQ-36 radar [125], both with edge slots in the narrow wall. Antenna systems with the slots in the broad wall of ridge loaded waveguides have been employed in several cases, e.g., the ARTHUR and Joint Stars projects [126-128]. In the latter the broad wall centered longitudinal slot is excited by alternating the height of the ridges. Scanned array systems using solid state transmit/receive module technology in combination with waveguide slot arrays have also been developed [129, 130].

6. CONCLUSION

Slot antennas and arrays have been investigated extensively in the literature. Theoretical solutions are available for a number of elements,

arrays, and coupling mechanisms. These antennas enjoy numerous applications since it is possible to design them precisely for the required performance and they offer low losses. Although there is a wealth of literature on waveguide-fed slot antennas and arrays, we could not include many excellent papers in the list of references because of the restriction on the size of this paper.

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