MODAL AND RADIATION PERFORMANCE OF RESONANT WAVEGUIDES

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Introduction:

This paper reviews the fundamental properties of resonant frequency selective guides (FSGs), [1]. These are constructed from periodic arrays that are frequency selective, and can be viewed as guiding structures at resonance and 'open' (leaky) elsewhere. We emphasise the importance of the array's resonance, which is an essential factor in the performance. The primary propagation and radiation characteristics of these structures are identified and discussed.

Propagation characteristics:

Computer models have been developed to predict the propagation and mode composition of FSGs acting as a waveguides with a circular cross section. Since these are primarily open structures, the determination of the complex propagation constant was examined. This information was necessary in order to ascertain the field distributions, which in turn affect their radiation properties. The latter may be of the form of leaky or end-fire due to guided modes. The structures employ doubly periodic elements of transverse dipoles and square loops shown in Fig. 1 and Fig. 2 respectively. The computer model produces the complex propagation constant and plots the aperture fields and field lines of the modes. The analysis is based upon the solution of the wave equation (in cylindrical co-ordinates) in conjunction with Floquet's theorem [2]. The fields have been set up as combinations of Bessel and Hankel functions. The Method of Moments (MoM) with rooftop look alike basis and testing functions has been used to determine the propagation (β) and attenuation (α) constants of a homogenous system. Once these were found the elements' currents and fields on the unit cell of the array were calculated by matrix inversion. Because of the large orders and arguments involved, necessary steps have been taken in the calculation of these functions. The propagation characteristics are obtained by a method, which chooses the appropriate Riemann surfaces. The latter is a crucial factor for bringing out surface, guided and leaky waves.

For the dipoles transverse to the length of the structure, it was found that the mode with the lower cut-off was a hybrid EH. HE types were also supported, but were highly attenuated. We have found distinct differences of the modes at different frequencies. Fig. 3 shows the real β and imaginary α propagation constants. The leakage is evident from the attenuation constant plot. It can be seen that firstly a surface wave appears, followed by a leaky (complex) wave. The monitoring of the attenuation constant and guiding modes supported at different frequencies have been extracted from the dispersion diagram by solving a homogeneous matrix system. The resonance is identified by observing the region of minimal leakage. The minima of the attenuation therefore correspond to guided waves. Square loop arrays (Fig. 4) produced minima with small attenuation constant. There is a correspondence between the transition regions (before and after the resonance) and the leaky behaviour of the structure. The effects of the periodicity and element dimensions have shown to affect the frequency and level of the leakage.

Linear dipoles exhibit weak guidance, but square loops have clearly identified guidance with small insertion loss. The dominant factor here is the resonance of the array, opening new avenues in leaky wave antennas. A study has been done on the latter in a related project. Unlike the traditional leaky wave antennas, Frequency Selective Structures have close element spacing, so there is little interference from grating lobes and scan blindness.

Radiation patterns:

This section describes the achievements of the radiation properties of FSGs. As well as the information given from the propagation characteristics a computer model has been developed to predict the radiation a finite model of a conical structure of dielectrically loaded dipole elements. The computer model predicts the boresight frequency response and radiation patterns of conical horns with dipole and crossed-dipole elements. The analysis considers a finite array of conducting elements coated with a thin arbitrary material. This may be dielectric or ferrite. Fig. 5 shows a drawing of the frequency selective horn antenna as well as the geometry of the dipole and its coat. The horn is fed with a cylindrical waveguide carrying the dominant EH_{11} hybrid mode, available from the propagation results discussed above. The conventional TE_{11} of a closed waveguide has also been used. This in turn has been modelled using a superposition of point sources at each element (segment) position. The Electric Field Integral Equation (EFIE) with an arbitrary coating, of relative permeability and permitivity ε_r and μ_r respectively, takes the following form:

$$E^i(r) = \frac{j\omega\mu_o}{4\pi}\left[\int_{-L/2}^{L/2} \mu_r \, I\hat{u}\, G(r - r_a)\, du_a - \int_{-L/2}^{L/2} (\mu_r - 1)\, I\hat{u}\, G(r - r_b)\, du_b\right] \quad (1)$$

$$+\frac{1}{4\pi\varepsilon_o}\left[\int_{-L/2}^{L/2} \frac{1}{\varepsilon_r}\left(\frac{-1}{j\omega}\frac{dI}{du_a}\right)\nabla G(r - r_a)\, du_a + \left(1 - \frac{1}{\varepsilon_r}\right)\int_{-L/2}^{L/2} \frac{1}{\varepsilon_r}\left(\frac{-1}{j\omega}\frac{dI}{du_b}\right)\nabla G(r - r_b)\, du_b\right]$$

I is the current flowing on the dipole of length L, G is the Green's function and E^i is the incident electric field. r_a and r_b denote vectors regarding the inner and outer radii of the cylindrical layer of the coating. The EFIE is transformed into a matrix system having segmented the elements. This system has been solved by a conjugate gradient iterative method and an elimination technique.

Varying the dielectric thickness has shifted the in band (resonance) of the antenna as well as broaden the bandwidth. This is depicted in Fig. 6, where it can be observed that the gain is also affected. The source and elements have been modelled in a finite manner by rendering the feeding aperture discrete. This approach ensures that the excitation is properly taken into account and will aid in matching the horn. The method also uses the MoM, but being finite large matrices are involved. The size of the matrix is typically 2,000 by 2,000 elements for a 10 cm long horn. The model predicted well the radiation performance on boresight, reproducing the high gain at the resonant frequency. Broadly the radiation patterns were reproduced, but there are some discrepancies of the sidelobe location and levels. This point requires further investigation. The radiated fields were calculated for the relevant mode. In addition, low crosspolarisation was achievable using tightly packed symmetrical element, such square loops and rings. Far field patterns of structures with dipoles, crossed dipole and loop-type elements with various orientations has been compared. Fig. 7 shows the boresight gain relative to the open-ended waveguide of an FSG with double squares. Although the band centre is near 15 GHz, the return loss is best at slightly below that frequency.

The element geometry has a noticeable influence on the gain and bandwidth of the FSG. Whereas dipole elements have narrow bandwidths, circular elements and square loops produce wider bandwidths associated with a gain increase. The bandwidth increase is related to the sensitivity of the internal reflections to the incident angles. Horns with cross dipoles produce two bands whose separation depends on the dimension of their individual arms The low band is dominated by a surface wave.

Closing comments:

Cylindrical resonant arrays of transverse dipoles and square loops have been introduced and studied. These structures exhibit attractive characteristics regarding their mode and radiation behaviour. They are also easy to construct and lightweight. The propagating modes are hybrid with symmetries in certain frequencies. Studies so far have shown that it is feasible to design a horn antenna to operate at two separate frequencies having similar beam patterns. The fruits of this effort would lead to producing multifunctional tasks with beam shaping and frequency scanning that, ultimately, would greatly enhance the performance of antennas in mobile and wireless network communication systems.

Publications

[1] VARDAXOGLOU, J.C., ROBINSON, A.J. and SEAGER, R.D.: 'Towards a new class of waveguiding structures and lightweight horn antennas using passive arrays', Proc. IEEE International Conference in Electromagnetics on Aerospace Applications, ICEAA, Torino, Italy, 1993, pp.343-346.

[2] VARDAXOGLOU, J.C.: 'Frequency Selective Surfaces: Analysis and Design', Research Studies Press (Wiley), Taunton, UK, 1996, ISBN 0 86380 196 X.

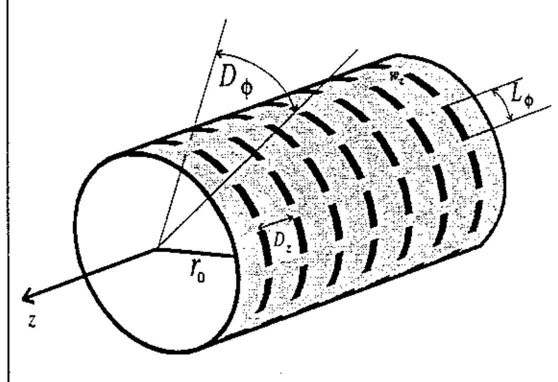

Fig. 1. A cylindrical array with transverse dipole elements.

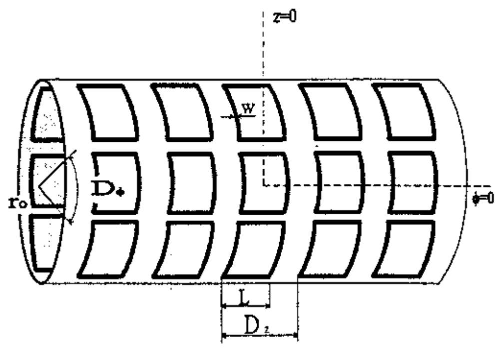

Fig. 2. FSG with square loop elements.

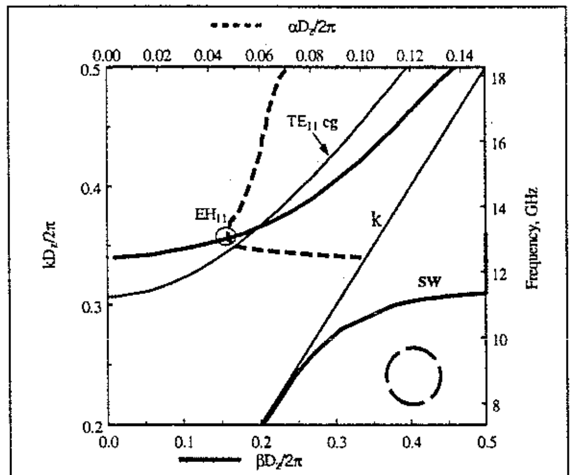

Fig. 3. Propagation curves of a singly periodic array of transverse dipoles, 4 dipoles in φ. (L= 11.75mm, D_{φ}= 12.33mm, D_z = 8.22mm apart, w = 0.1 D_z).

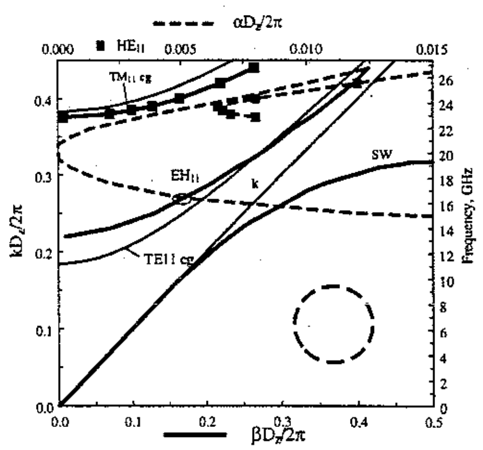

Fig. 4. Propagation and attenuation plots for an FSG with 10 square loops along φ. (D_{φ} = D_z= 4932mm, L = D_z/ 1.05 = 4.7mm, r_0 =7.85mm, w=L/7 = 0.67mm).

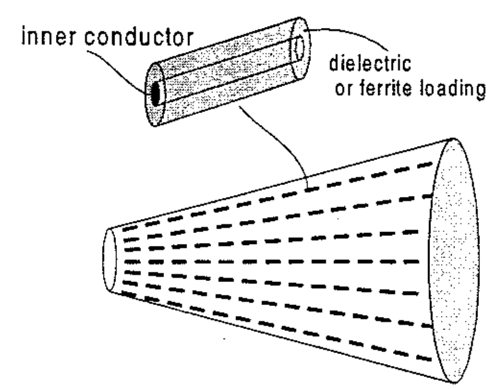

Fig. 5 Geometry of horn antenna and dipole loading

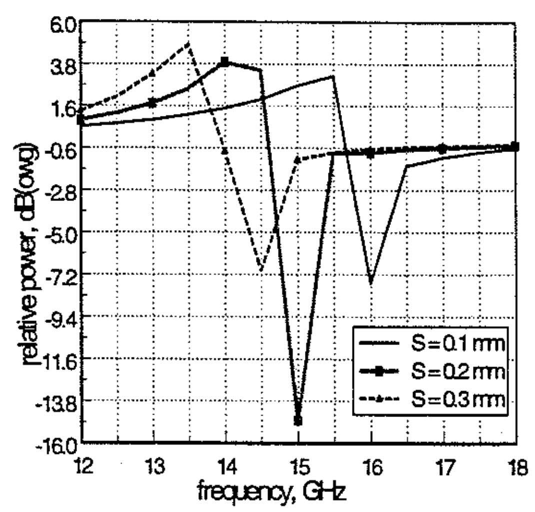

Fig. 6. Effect of dielectric loading on frequency response

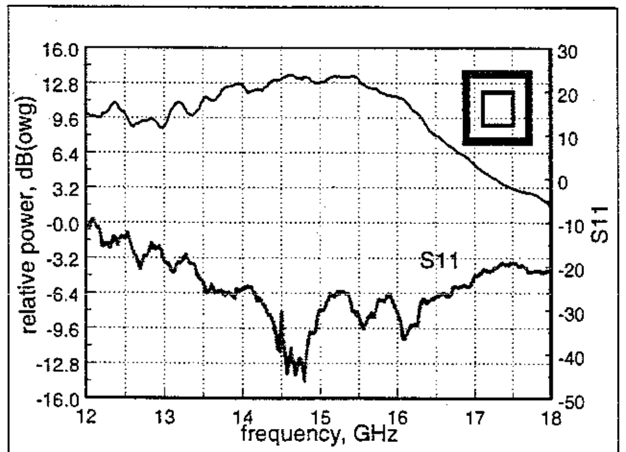

Fig. 7. Forward transmission and S11 of horn with double square loops.