Optimum Design of SIW Longitudinal Slot Array Antennas with Specified Radiation Patterns

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Abstract **─** In this paper, an optimum design is presented for substrate integrated waveguide (SIW) longitudinal slot array antennas based on the method of least squares (MLS). Elliott's design procedure for dielectric filled waveguides is considered, taking into account the internal and external mutual couplings. The MLS error function is a multi-term function based on design goals, including specified radiation patterns and matching of the input impedance. We use the hybrid method of genetic algorithm-conjugate gradient for the error function minimization. This approach is very effective because of combining the "pattern synthesis" with "impedance matching" and "calculation of array parameters". This procedure increases the speed of design as well as synthesizing patterns with specified characteristics. The MLS design results and those obtained by HFSS and CST simulation software are in good agreement and verify the accuracy of the proposed method.

Index Terms **─** MLS, optimization, slot array, and SIW.

I. INTRODUCTION

Waveguide slot array antennas have many applications in communication and radar systems [1-2], due to their significant advantages such as: high efficiency, high gain, mechanical strength, and the absence of spurious radiations from the feed system. The most common configuration for slot array antennas is the longitudinal slots due to low cross polarized levels. Using Elliott's design procedure [3-5], a slot array can be accurately synthesised.

SIW is a new structure proposed to replace the conventional rectangular waveguide [6-10]. Having the benefits of rectangular waveguides, SIWs are easily fabricated, have lower cost, smaller size, lower weight, and are easier integrated with other planar circuits. As a result, SIW is a good structure for microwave and millimeter-wave applications.

Using the equivalent waveguide for SIW, one can use Elliott's design procedure to design the SIW longitudinal slot array antennas. SIWs have considerably lower height than common rectangular waveguides. Thus, the internal mutual coupling of higher order modes is significant. Consequently, it is suitable to use the design formulas of [5], which account for the three sources forming the field of slots, namely: incident field (TE_{10}), external, and internal coupling.

This paper presents an optimum method for the design of SIW longitudinal slot array antennas, based on the method of least squares (MLS). An error function is formulated consisting of three terms, namely those for the design equations, input impedance matching, and pattern synthesis. The error function is then minimized with respect to the design parameters (namely slot lengths, offsets, and excitation) using the hybrid method of genetic algorithm and conjugate gradient method.

II. DESIGN PROCEDURE

A. SIW design

First, the SIW should be designed for the desired operating frequency. The structure is

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shown in Fig. 1 where *d* is the diameter of metallic vias, *p* is the distance between them, *h* is the height and a_{SIW} is the width of SIW. There is a region in the plane of d-p where the SIW is equivalent to a metallic rectangular waveguide and has similar guiding characteristics [7].

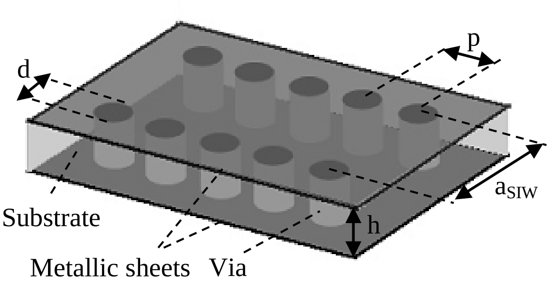


Fig. 1. SIW structure.

This region has the following properties:

1- It does not present any band-gap in its operating bandwidth ($p < 0.25\,\lambda_c$).
2- It has negligible leakage loss ($p \leq 2d$).
3- It is physically realizable ($p > d$).

where, λ_c is the cutoff wavelength of the TE_{10} mode. An accurate empirical formula has been proposed in [8, equation 21], which gives an error of less than 1% for the condition p>1.2d. Consequently, the region can be defined as:

$$p < 0.25\lambda_c \,. \tag{1}$$

$$1.2d < p \leq 2d \,. \tag{2}$$

The operating frequency is set between the cutoff frequency of TE_{10} and TE_{20} modes by choosing the correct width for the SIW (a_{SIW}). This, results in a single mode waveguide (only TE_{10}).

B. Calculation of the isolated slot admittance

The isolated admittance of a slot (Y/G_0) can be obtained by different methods such as: direct measurements, analytical calculations or computer aided simulations. We have used a finite-element commercial software (HFSS) due to its simplicity and lower cost.

The simulation model is shown in Fig. 2 in which the admittance matrix at the test port and the center of slot are equivalent. Having done the simulation, one could plot the parametric curves of Y/G_0 with respect to the slot length ($2l$) and offset (x); and then obtain a closed form function for the normalized admittance of the isolated slot. The admittance characteristics exhibit stronger dependency on the slot parameters in the SIW with much thinner height [10]. Consequently, to achieve high accuracy in curve fitting, polynomial functions with steps *0.1mm* for *2l* are used. The closed forms of real and imaginary parts of Y/G_0 are:

$$\begin{gathered}(Y/G_0)_{real} = r_1(x)(2l) + r_0(x)\,, \\ r_i(x) = t_{i2}x^2 + t_{i1}x + t_{i0}\;, \quad i = 0{,}1\,. \end{gathered} \tag{3}$$

$$\begin{gathered}(Y/G_0)_{imag} = i_1(x)(2l) + i_0(x)\,, \\ i_i(x) = u_{j2}x^2 + u_{j1}x + u_{j0}\;,\; i = 0{,}1\,. \end{gathered} \tag{4}$$

For example, at the frequency of $f=10GHz$ according to the SIW design rules mentioned in the previous section, the following parameters are considered: $d=0.5mm$, $p=0.9mm$, $a_{SIW}=15.4mm$, $\varepsilon_r=2.2$ and $h=1.5mm$. The metallic sheet thickness is *0.1 mm* and the slot width is *0.5 mm*. The resulted curves are shown in Fig. 3.

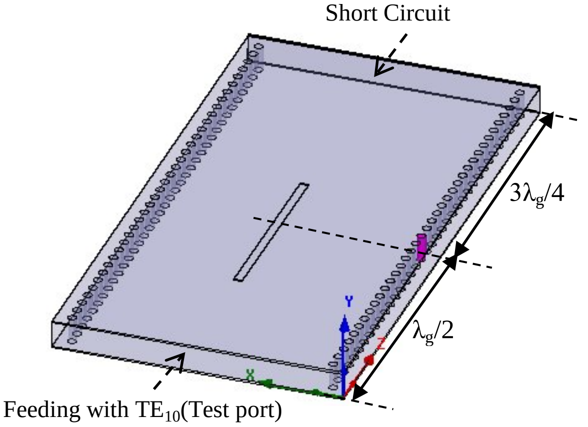


Fig. 2. The simulation model used to calculate the Y/G_0

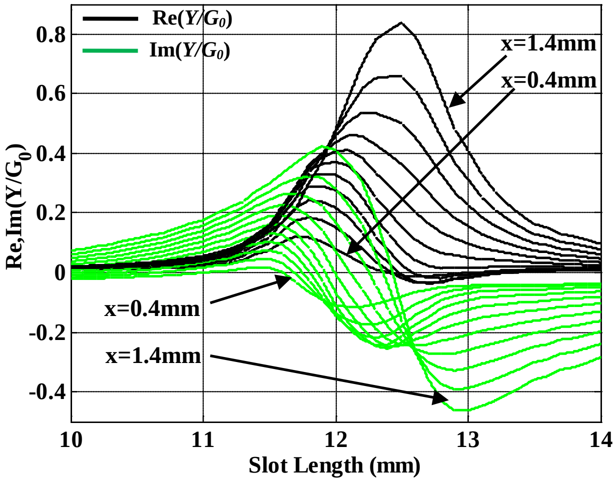


Fig. 3. Normalized admittance of an isolated slot with steps *0.1mm* for offset.

C. The error function

The total error function is formulated according to the design goals, consisting of three terms, namely one for the two design equations, one for the impedance matching and the third for the pattern synthesis. Then:

$$\varepsilon_{total} = \varepsilon_{design\_equ} + \varepsilon_{input\_match} + \varepsilon_{synthesis}\,. \quad (5)$$

1. The error function for design equation

Design equations for a linear array of slots with standing-wave excitation is presented in [5]. The error function for design equations is:

$$\varepsilon_{design\_equ} = W_1 \sum_{n=1}^{N}\sum_{m=1}^{N} \left| \frac{|f_n| \left(\dfrac{2 f_m^2}{Y_m / G_0} + MC_m \right)}{|f_m| \left(\dfrac{2 f_n^2}{Y_n / G_0} + MC_n \right)} - \frac{V_n^s}{V_m^s} \right|^2 , \quad (6)$$

where, W_1 is the weighting function. Definitions of all other symbols are found in [5]. This equation is obtained by setting the two fundamental design equations equal, and dividing the terms corresponding to the mn'th slot by the ij'th slot in the array.

2. The error function for impedance matching

Since slot spacings are half a wavelength, the input admittance of the equivalent transmission line model is written as the sum of all the active admittances of slots:

$$Y_{in} = \sum_{n=1}^{N} \frac{Y_n^a}{G_0} = \sum_{n=1}^{N} \frac{2 f_n^2}{Q_n} = 1 + j0\,. \quad (7)$$

So we can write this part of the error function as follows:

$$\varepsilon_{input\_match} = \varepsilon_{real} + \varepsilon_{imag}$$
$$= W_2 \left| \mathrm{Re}(Y_{in}) - 1 \right|^2 + W_3 \left| \mathrm{Im}(Y_{in}) \right|^2 . \quad (8)$$

3. The error function for pattern synthesis

The pattern of the linear array (including the element factor due to slot):

$$S(\theta) = \sum_{n=1}^{N} \left| \frac{V_n^s}{V_1^s} \right| s_n(\theta) e^{jn(k_0 \frac{\lambda_g}{2} \cos\theta)} , \quad (9)$$

where, $k_0 = 2\pi/\lambda_0$ and $s_n(\theta)$ is the element factor of n'th slot is derived by making the slot equivalent to a dipole of length $2l_n$:

$$s_n(\theta) = \frac{\cos(kl_n \cos\theta) - \cos(kl_n)}{\sin\theta}\,. \quad (10)$$

The error function of pattern synthesis is written as:

$$\varepsilon_{synthesis} = W_4 \left| S(\theta) - S_{spec}(\theta) \right|^2 , \quad (11)$$

where, $S_{spec}(\theta)$ is the specified pattern with desired characteristic such as sidelobe level, gain and beamwidth.

4. Minimization technique of the error function

The MLS error function of the slot array design is a very complex multi-variable function. Finding optimum solutions is a challenging problem due to the presence of many extrema. Global optimization (GO) methods such as genetic algorithm (GA) or local optimization (LO) methods such as conjugate gradient (CG) cannot be used solely since: 1. GO methods may require long processing time, since they iteratively evolve toward the exact solution by means of probabilistic rules. They also devote more effort to search for the global optimum region instead of finding the precise position of the local optimum. 2. LO methods are in general very fast, but they may not be well-suited to this work because they are unable to escape from local minima in a multi-extrema problem. Therefore, the high accuracy and fast speed is the direct result of hybridization of global and local optimizers.

We have used the hybrid GA-CG method in the current work. This algorithm is developed using MATLAB optimization functions. The optimization starts with the GA optimizer with a rough initial value and continues for several iterations. The population size used for the GA optimization is 60, the type of cross over function is "Scattered", the mutation function is "Adaptive feasible" and the number of generations is usually selected between 10-30. The results obtained by the GA optimizer are used as suitable initial values for the CG optimizer which is sensitive to the starting point. The number of iterations which provides the optimum result is usually 200-300.

Constraints applied to the design parameter (length and offset of slots) are originated from physical limitations (waveguide dimensions) and radiation characteristics (resonance length of slot). The values of lengths are constrained to the range of (10 to 14mm) and offsets constrained to the range of (0.2 to 1.5mm).

The computation time for the two examples given in this paper is in the order of a few minutes, while optimization of same examples using optimizers in full-wave simulation softwares such as Ansoft HFSS takes several days. It should also be mentioned that achieving all of the design goals (array pattern synthesis and input matching) is a cumbersome task in full-wave simulation software.

III. RESULTS

For verification purpose, two SIW linear array antennas at the frequency of *f=10GHz* are designed. SIW structure parameters and the normalized admittance of the isolated slot are given in section II. Width of the equivalent waveguide for the SIW is obtained *15.0536mm.*

First array is considered with seven slots and it is aimed to give a SLL of -20dB. This is done by setting an upper and lower limit for the side lobes at specific angles θ, so that the pattern stays within these limits. Consequently, the error function for the pattern synthesis is:

$$\varepsilon_{synthesis} = W_4^{upper} \sum_{m=1}^{M} \left| S(\theta_m) - h_m^{upper} \right|^2 + W_4^{lower} \sum_{m=1}^{M} \left| S(\theta_m) - h_m^{lower} \right|^2 , \qquad (12)$$

where, h_m^{upper} and h_m^{lower} are the upper and lower limits of SLL of the desired pattern, respectively and θ_m denotes an angle between 0 to 180 degree. Applying the Method of Least Squares to the mentioned array, results in $S_{11}= -11dB$ at *f=10GHz*. Comparing the results obtained by the MLS with full-wave simulations for several examples of linear slot array, shows that setting the desired input admittance as $Y_{in}=0.7+j0.3$ (instead of ideal value of $Y_{in}=1+j0$) in the error function, results in better impedance matching. The need for such an adjustment in MLS design goal is mainly due to two factors; the approximations in the Elliott's design formulas (low height of waveguide) and in making the SIW equivalent to a conventional metallic waveguide. It should be noted that the value of Y_{in} stated above, is suitable for the design of almost every antenna array of this type. The obtained slots parameters (Fig. 4) are shown in Table 1. Comparing the results obtained by MLS with those from HFSS and CST simulation (Fig. 5) shows a good agreement.

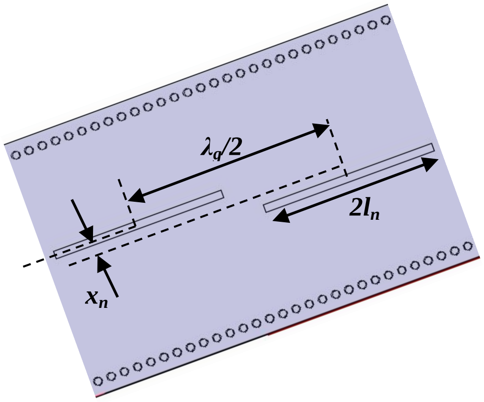


Fig. 4. Slot parameters.

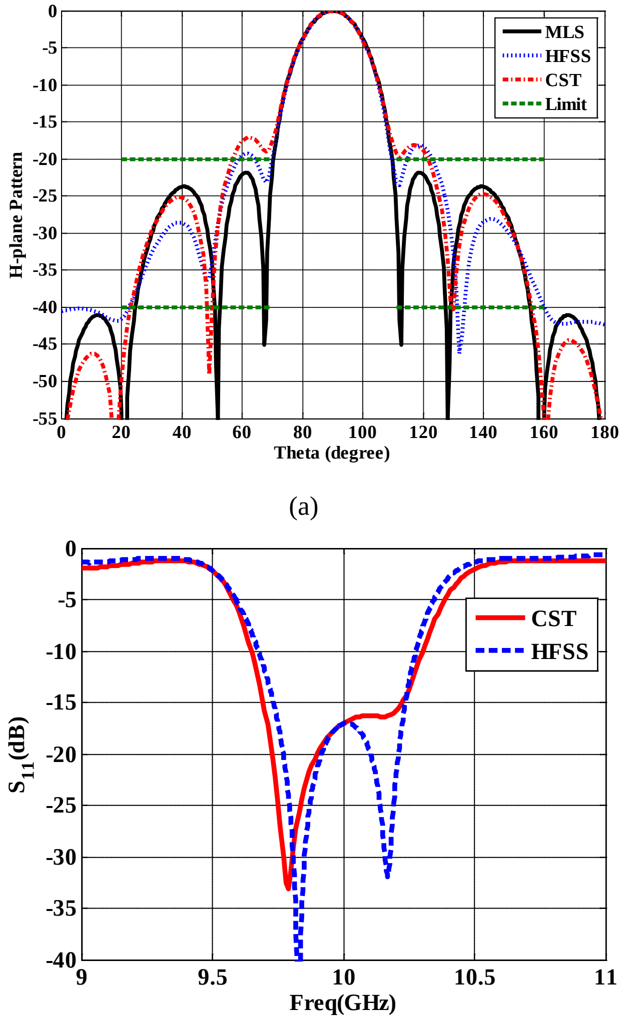
Second array is considered with fourteen elements to achieve a high gain. It is known that Dolph-Chebyshev's method for pattern synthesis, provides a minimum beamwidth for a given sidelobe level, making it a suitable candidate for directive beam pattern design. Therefore, the error function for pattern synthesis is:

$$\varepsilon_{synthesis} = W_4 \left| S(\theta) - S_{dolph}(\theta) \right| , \qquad (13)$$

where, S_{dolph} is Dolph-Chebyshev's pattern. In this example, the element factor is not included in the error function of pattern synthesis to simplify the optimization procedure. However it is considered in the final MLS pattern. The obtained slots parameters from MLS are shown in Table 2 and the results are shown in Fig. 6. A good agreement is seen between MLS and the simulation results.

Table 1: MLS results

Seven Elements Linear Array							
n	$\lvert x_n \rvert$	$2\ell_n$	$\lvert V_n^s / V_1^s \rvert$	n	$\lvert x_n \rvert$	$2\ell_n$	$\lvert V_n^s / V_1^s \rvert$
1	0.581	11.070	1.000	5	0.823	11.203	1. 683
2	0.752	11.042	1.276	6	0.752	11.042	1.276
3	0.823	11.203	1.683	7	0.581	11.070	1.000
4	0.879	11.226	1.836				



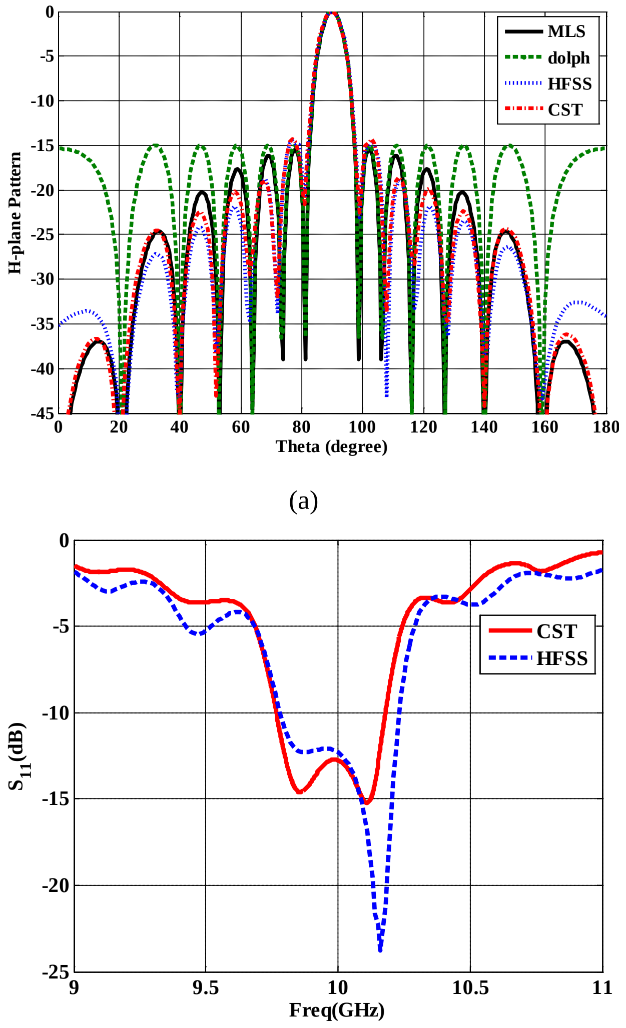
(a)

(b)

Fig. 5. A seven element linear array, (a) H-plane pattern, (b) S_{11} (dB).

Table 2: MLS results

Fourteen Elements Linear Array							
n	$\lvert x_n\rvert$	$2\ell_n$	$\lvert V_n^s/V_1^s\rvert$	n	$\lvert x_n\rvert$	$2\ell_n$	$\lvert V_n^s/V_1^s\rvert$
1	0.475	11.359	1.000	8	0.611	11.068	0.686
2	0.664	10.794	0.440	9	0.609	11.055	0.661
3	0.555	11.000	0.509	10	0.592	11.049	0.630
4	0.585	11.028	0.582	11	0.586	11.018	0.570
5	0.594	11.044	0.626	12	0.552	11.006	0.513
6	0.608	11.062	0.669	13	0.666	10.786	0.435
7	0.613	11.064	0.682	14	0.474	11.360	1.000



(a)

(b)

Fig. 6. A fourteen element linear array, (a) H-plane pattern, (b) S_{11} (dB).

VI. CONCLUSION

A very effective method is presented for the design of SIW slot array antennas. The proposed method has been applied to the design of seven and fourteen slot array antennas with specified radiation patterns. The good agreement between the MLS design results and those are obtained by HFSS and CST simulation software verifies the accuracy of the proposed method. The hybrid optimization method of GA-CG has the advantage of giving results in a very short computation time.

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