Optimization and Simulation of Helix loaded with Dielectric Dispersion Characteristics using TLBO Algorithm

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Abstract

In this paper, an analytical theory of dispersion characteristics for Helix loaded with Dielectric (HLWD) has been investigated numerically for fundamental as well as higher-order Hybrid modes (HE and EH) for guided electromagnetic wave propagation. The appropriate value of helix pitch angle, dielectric radius and dielectric constant were found out using Teaching Learning Based Optimization (TLBO) with an aim to get wide single-mode wave propagation bandwidth. This structure can be used to determine radiation characteristics of axial mode helical antenna where radiation is coming out from the end of the aperture. It can be used as a highly directive end-fire antenna that finds potential application in satellite communication.

1. Introduction

The boundary value problem arising in the propagation of helix-based slow-wave structure has been solved mainly by two popular models: sheath and tape helix. Beginning with Sensiper's fundamental work [1] to the publication of [2], all published derivations [3–5] of the dispersion characteristics of electromagnetic waves guided by a helix-based slow-wave structure were based on the Bessel I function inside the core medium and also considered infinitesimal thickness of helix. The Bessel I function was chosen due to the air-filled core region. However, in the case of a dielectric-filled core region, the Bessel I function should be replaced with the Bessel J function [6]. Though the previous work discusses the dispersion properties of the radially thick helix, but it was limited to the air-filled inner region.

In the paper, an investigation of the modal and dispersion characteristics of HLWD is presented with a Muller numerical method. The helix of the proposed HLWD has radial thickness. The three important parameters for this type of structure are helix pitch angle, helix radius, and dielectric medium. The value of these parameters is optimized by a new efficient Teaching Learning Based Optimization (TLBO) algorithm. This method is proposed to evaluate the characteristics equation of HLWD as an error function, and the optimized parameters are helix pitch angle, helix radius and dielectric constant to achieve the maximum value of wide mono mode propagation bandwidth.

2. Characteristics Equation of HLWD

Figure 1 depicts the schematic diagram of HLWD, which has been described in three regions: the dielectric medium as the innermost region, the helix as the middle region, and free space as the outermost region.

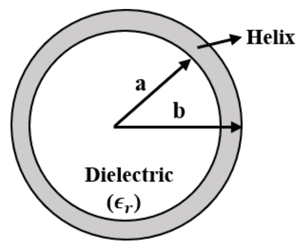

Figure 1. Geometry of HLWD

The characteristic equation for hybrid modes can be obtained by applying the continuity boundary conditions of tangential electric and magnetic fields at r = a and b [2] which is shown below:

$$\left(1-\frac{n\beta cot\psi}{k_{Ci}^2 a}\right)^2 \frac{J_n(k_{ci}a)k_{ci}}{J_n^{'}(k_{ci}a)} + \left(1+\frac{n\beta cot\psi}{k_{Ce}^2 b}\right)^2 \frac{K_n(k_{ce}b)k_{ce}}{K_n^{'}(k_{ce}b)} - k_0^2 cot^2\psi \left[\frac{\varepsilon_r J_n'(k_{ci}a)}{k_{ci}J_n(k_{ci}a)} + \frac{K_n'(k_{ce}b)}{k_{ce}K_n(k_{ce}b)}\right] = 0 \quad (1)$$

Where $a, (b-a)$ and ψ are the dielectric radius, radial thickness and pitch angle of helix respectively.
Here, axial components in z direction is used to define wave propagation characteristics, k_0 is the free space propagation constant. J_n and K_n are Bessel function of first kind and modified Bessel function of the second kind, respectively, where n is the azimuthal Eigen value of the fields, k_{ci} and k_{ce} are the propagation constants in the transverse direction and expressed as follows:

$$k_{Ci}^2 = k^2 - \beta^2 \quad (2)$$

$$k_{Ce}^2 = \beta^2 - k_0^2 \quad (3)$$

$$k^2 = k_0^2 \mu_0 \epsilon_r \quad (4)$$

The axial propagation constant (β) is calculated from the above equation, and this value is used in the following section to compute the normalized phase constant (β/k_0).

3. TLBO: An Optimization Approach

The Teaching-learning-based optimization (TLBO) [7] is an algorithm inspired by a classroom teaching method similar to the nature-inspired evolutionary algorithm. There are mainly two phases: 1) Teacher Phase (2) Learner Phase (Student Phase). A population of learners is considered in this optimization technique, and different subjects supplied to the learners are considered as different design variables of the optimization problem, and a learner's result is equivalent to the optimization problem's 'fitness' value. The instructor gives the finest solution to the entire population. The flow chart of the algorithm is shown in Figure 2 [8].

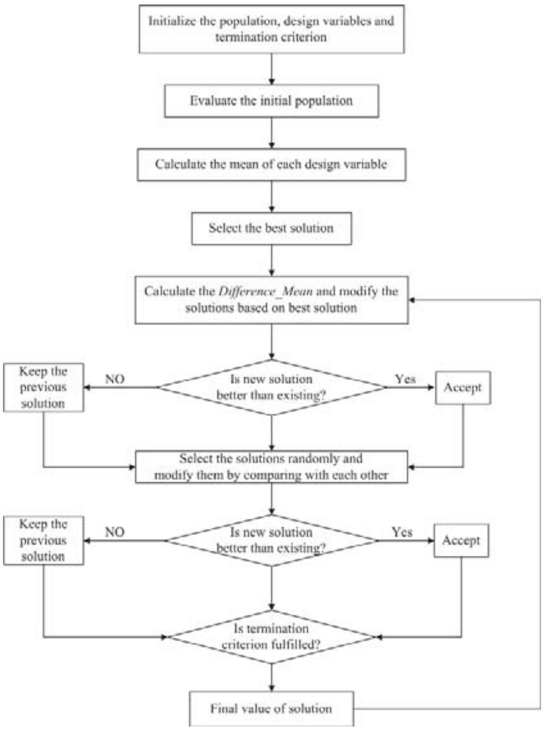

Figure 2. Flow chart of TLBO Algorithm

In the teacher phase, students initially obtain information from a teacher to improve the class's mean outcome. Learners learn from the teacher in this phase, and the teacher tries to improve the result of the other individual (P_i) by raising the classroom's mean result (P_{mean}) towards the teacher's result ($P_{teacher}$). Two random variables are generated in the range 0 and 1, which is stored in the variable:

$$P_{new} = P_i + r.(P_{teacher} - T_f.P_{mean}) \tag{5}$$

where P_{new} and P_i are the new and existing solution of an i^{th} individual, and T_f is a teaching factor which can either be 1 or 2.

In the learner phase, students acquire knowledge with mutual discussion and interaction with one another. The expertise learner will provide new information to other learners who have lesser information compared to him. During this step, P_i engages with another student P_j at random to broaden his or her expertise. If P_j has greater knowledge than Pi after learning, Pi is shifted towards P_j.

$$P_{new} = P_i + r\,(P_i - P_j)\ \text{if}\ f(P_i) < f(P_j) \tag{6}$$

$$P_{new} = P_i + r\,(P_j - P_i)\ \text{if}\ f(P_j) < f(P_i) \tag{7}$$

The population has accepted the improved new solution, P_{new}, and the process will continue until the best-fit condition is found. TLBO has become a popular optimization method due to its ease of implementation and great efficiency, and it has been successfully applied to a variety of real-world issues. The algorithm is implemented for six students in this publication.

4. Simulation Results and Discussions

To obtain the normalized propagation constant (β/k_0) as a function of helix radius, the dispersion relation is solved numerically by complex root search Muller method using MATLAB [9]. The dispersion equation (1) is used here as fitness function of TLBO algorithm that was used to optimize the HLWD guided mode characteristics. Here the population (No. of Students) is 6 and design parameters are helix pitch angle (upper limit-30 and lower limit-15), helix inner radius a (upper limit-15 mm and lower limit-10 mm) helix outer radius b (upper limit-15 mm and lower limit-12mm) and dielectric constant (upper limit-10 and lower limit-4) of the rod. These four design parameters are optimized in the TLBO algorithm to find out the best possible output for lower-order hybrid operating modes (like HE and EH). The main objective is to find out wide single-mode propagation bandwidth so that the fundamental mode can be operated for a wider frequency range. The optimization algorithm code is developed in MATLAB and within 20 iterations we can get the optimum result at $\Psi = 17^0$, a= 10 mm, b = 13 mm, and $\varepsilon_r = 4$ for HLWD. Figure 3 describes the dispersion characteristics of the lower order of hybrid (HE and EH) mode. The cutoff frequencies for guided modes are mentioned in Table 1. The obtained propagation bandwidth for fundamental HE and EH mode are 9.6 GHz and 8.5 GHz respectively.

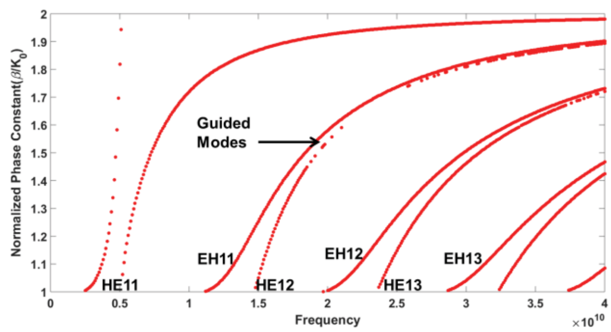

Figure 3. Dispersion Characteristics of normalized phase constant for a guided mode region.

Now, the variation in radius is taken into consideration. Up to this, we have observed that the TLBO algorithm is optimized at a lower limit of radius value to get wide single-mode propagation bandwidth. Therefore, the designed antenna could be operated at a higher frequency region by decreasing the value of radius. In the next simulation, the design parameters are taken as helix pitch angle (upper limit-30 and lower limit-15), helix inner radius a (upper limit-10 mm and lower limit-05 mm) helix outer radius b (upper limit-10 mm and lower limit-07 mm), and dielectric constant (upper limit-10 and lower limit-4) of the rod. Figure 4 describes the dispersion characteristics of the lower order of hybrid (HE and EH) mode. The optimized result is obtained at $\Psi = 15^0$, a= 5 mm, b = 8 mm, and $\varepsilon_r = 4$ for HLWD. The cutoff frequencies for guided modes are mentioned in Table 1. The obtained propagation bandwidth for fundamental HE and EH mode are 19.3 GHz and 17.4 GHz respectively. This parameter is helpful to design axial mode (guided mode) helical antenna based on the requirement of mode propagation. The dispersion characteristics give the exact value of normalized phase and attenuation constant therefore overall behavior of electromagnetic wave and field propagation can be evaluated.

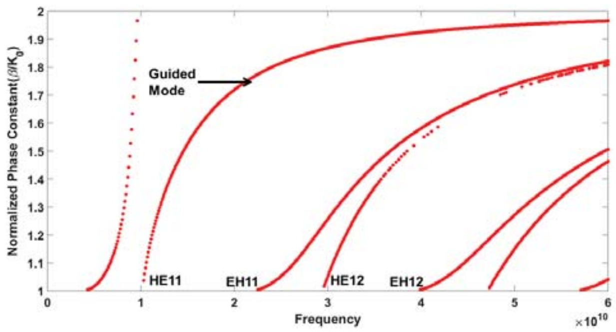

Figure 4. Dispersion Characteristics of normalized phase constant for a guided mode region.

Table 1. The cut-off frequency for various HE and EH modes

$\varepsilon_r = 4$	$\Psi = 17^0$, a= 10 mm, b = 13 mm,	$\Psi = 15^0$, a= 5 mm, b = 8 mm,
HE_{11}	5.2 GHz	10.3 GHz
EH_{11}	11.2 GHz	22.5 GHz
HE_{12}	14.8 GHz	29.6 GHz
EH_{12}	19.7 GHz	39.9 GHz
HE13	23.7 GHz	47.3 GHz
EH13	28.7 GHz	57.1 GHz

Next, the effect of the dielectric constant is taken into consideration. With the decrement in the dielectric constant value, from $\varepsilon_r = 4$ to 2, it is observed that higher-order HE mode is absent. The design parameters are helix pitch angle (upper limit-30 and lower limit-10), helix inner radius a (upper limit-15 mm and lower limit-10 mm) helix outer radius b (upper limit-15 mm and lower limit-12mm), and dielectric constant (upper limit-10 and lower limit-2) of the rod. The optimum result is shown in Figure 5 at $\Psi = 10^0$, a = 10 mm, b = 13 mm and $\varepsilon_r = 2$ for HLWD. Therefore, it is concluded that the helix should be operated at a lower dielectric value to achieve a wide propagation bandwidth. The obtained bandwidth for fundamental HE mode is 25.6 GHz.

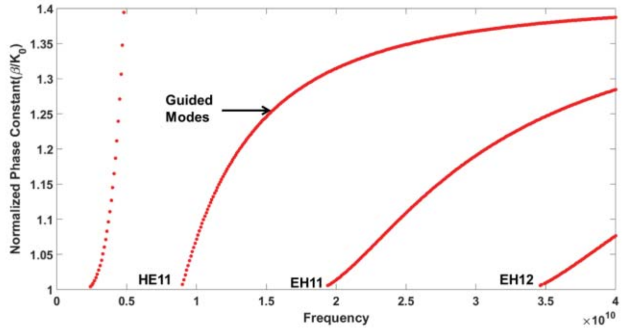

Figure 5. Dispersion Characteristics of normalized phase constant for a guided mode region.

Furthermore, similar results are shown for the lower value of the radius, from a= 10 to 5 mm, by keeping other parameter values as it is as per the previous simulation. The optimum result at $\Psi = 10^0$, a= 8 mm, b = 5 mm and $\varepsilon_r = 2$ for HLWD is shown in Figure 6. Helix should be operated at a lower dielectric value to achieve a wide propagation bandwidth. Based on the application, the dielectric constant value should be chosen. By increasing the dielectric constant value, the cutoff value is shifted to a lower frequency region.

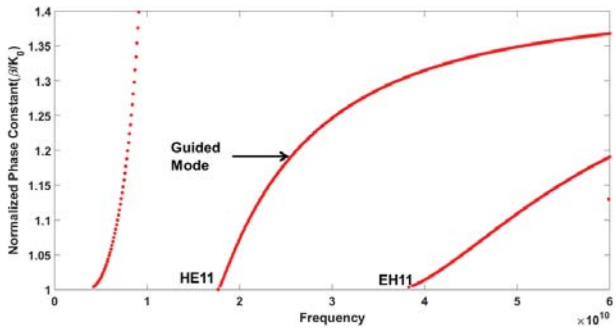

Figure 6. Dispersion Characteristics of normalized phase constant for a guided mode region.

Table 2. The cut-off frequency for various HE and EH modes

$\varepsilon_r = 2$	$\Psi = 10^0$, a= 10 mm, b = 13 mm	$\Psi = 15^0$, a= 5 mm, b = 8 mm
HE_{11}	9 GHz	17.7 GHz
EH_{11}	19.4 GHz	38.3 GHz
HE_{12}	34.6 GHz	NP

*NP = not present

5. Conclusion

The guided mode characteristic of HLWD was theoretically investigated for higher-order Hybrid Modes (HE-EH) which were defined by the real value of phase constant. With TLBO Algorithm, optimization was performed on the HLWD with design parameter helix pitch angle, helix radius and dielectric constant to obtain wide single-mode propagation bandwidth. It was also analyzed that optimization of waveguide always converges at the lower limits of radius and dielectric constant. Moreover, the dielectric constant plays a crucial role in mode propagation and generation.

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