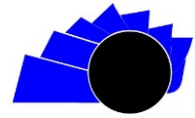




UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Visión Electrónica

<https://revistas.udistrital.edu.co/index.php/visele>





VISIÓN ELECTRÓNICA

A RESEARCH VISION

Index profile model for the synthesis of few-mode multimode optical fibers

Modelo de perfil de índice para la síntesis de fibras ópticas de pocos modos

Manuel Romero-Peña ¹, Gustavo Adolfo Puerto-Leguizamón ²

INFORMACIÓN DEL ARTÍCULO

Historia del artículo:

Enviado: 13/04/2024

Recibido: 27/04/2024

Aceptado: 10/07/2024

Keywords:

Index

Profile

Bandwidth

Mode

Multimode

Parabolic



Palabras clave:

Índice

Perfil

Ancho de banda

Modo

Multimodo

Parabólico

ABSTRACT

This paper presents the development of a model that allows the calculation and design of multimode optical fibers of few modes, from the mechanical parameters that describe the geometry of the parabolic index profile and the electromagnetic behavior in this guided transmission medium. For this purpose, a system of equations has been developed based on the performance evaluation metrics of an optical fiber and an independent variable that is adjusted through an optimization algorithm to evaluate the best values of bandwidth, dispersion, and propagated modes in multimode optical fiber propagation windows.

RESUMEN

Este documento presenta el desarrollo de un modelo que permite el cálculo y diseño de fibras ópticas multimodo de pocos modos a partir de los parámetros mecánicos que describen la geometría del perfil de índice parabólico y el comportamiento electromagnético de este medio de transmisión guiado. Para ello se han conformado sistemas de ecuaciones basados en las métricas de evaluación de desempeño de una fibra óptica y una variable independiente que es ajustada por medio de un algoritmo de optimización para evaluar los mejores valores de ancho de banda, dispersión y modos propagados en las ventanas de propagación de fibra óptica multimodo.

¹ Electronic Engineer, Universidad Distrital Francisco José de Caldas, Colombia. E-mail: mromerop@udistrital.edu.co

² Full Time Professor: Universidad Distrital Francisco José de Caldas, Colombia. E-mail: gapuerto@udistrital.edu.co

1. Introduction

Over the past few years, a new fiber material has been developed with the potential of making better use of communication channels compared to the mono-mode fiber used in most network links. The new material is a multimode fiber, yet it contains fewer modes than the conventional fiber.

Depending on its primary feature, which defines the name of the same fiber, it offers the possibility to adapt to the phenomena seen in standard multimode fibers.

According to [1], [2], [3], and other articles, the number of modes that can be propagated by this type of fiber depends on the radius of its core, as the wavelength with which a beam of light is propagated may or may not enter the fiber given this parameter. This occurs when the propagation of the fundamental mode LP01 [4] takes place in any optic fiber.

As seen in [5], the intrinsic parameters used to design fibers with fewer modes include the radius, the index profile, and the fiber length [6][7]. In essence, the radius of the core enables to modify the number of propagated modes [3][8][9], the index profile also has an effect over the number of modes and the index value of the fiber; as such, the step-based nature of the geometry can account for a higher number of modes compared to its gradual counterpart [1] [10]. A higher number of modes is also related to an increase in their modal dispersion [11][12][13] and the distance travelled by the modes to be transported [1].

The measurement of modes and signal quality in optic fibers takes into consideration the attenuation, dispersion, and latency of modes, among other variables. Attenuation can significantly affect the length with which a link can be established, and it increases proportionally with the distance [14], meaning that the attenuation factor is measured in $\frac{dB}{km}$ [3][8]. Dispersion is one of the most important factors regarding the transmission of an information signal.

This factor is categorized into two types: modal and chromatic. Modal dispersion is mostly present in optic fibers that handle more than one mode, and chromatic dispersion affects all fibers [3][8]. The latency between modes is measured based on the propagation time of the modes throughout a section of fiber [5].

2. Materials and methods

2.1. Propagation modes

When a fiber can tolerate numerous modes, it is called a multimode fiber. The number of modes is given by the normalized frequency [15] [16].

$$V = \frac{2\pi d}{\lambda} \sqrt{n_1^2 - n_2^2} \quad (1)$$

where d is the diameter of the fiber and λ is the wavelength of the optic fiber

Based on equation 1, the number of modes propagated by a step-index fiber can be determined as:

$$M = \frac{V^2}{2} \quad (2)$$

The number of modes in a step-index optic fiber can be determined through equation 3, The dependance on the variable λ is noticeable, since it defines the geometry of the profile:

$$M = \frac{\alpha}{\alpha + 2} a^2 k_0^2 \Delta \quad (3)$$

2.1.1. Index difference

The parameter Δ is defined as the difference between the indexes of the core and the coating, where the typical values of the multimode fibers vary between 1% and 3%, so the value of Δ is significantly lower than 1 [15][17].

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \quad (4)$$

2.1.2. Wave number

It is the magnitude that represents the number of cycles completed by the wave per distance unit. It is calculated by dividing 2π by the wavelength.

$$k = \frac{2\pi}{\lambda} \left[\frac{\text{rad}}{\text{m}} \right] \quad (5)$$

In the field of physics, the wave number is a parameter of the stationary wave equation (equation 6) that multiplies the position within the sinus argument. It is a characteristic value of this type of wave.

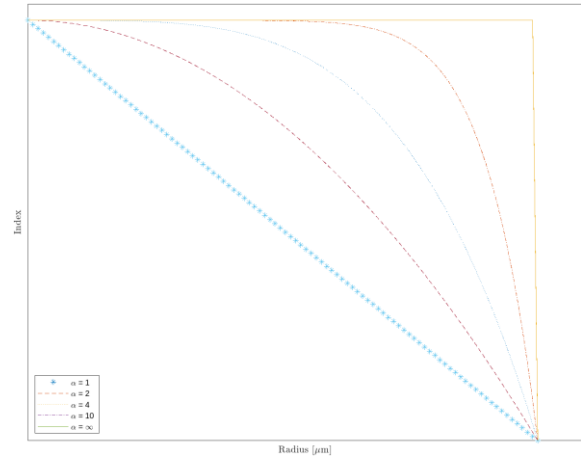
$$y = 2A \sin(k_0 x) \cos(\omega t) \quad (6)$$

2.1.3. Alpha equation

The multimode fibers of gradual index can be defined through equation 7, which can be used to describe the geometric behavior of the core index in terms of the variation of the radius through the core (parabolic profile) [18], based on a constant value of the fiber coating index. The fiber profile has a cone shape when the parameter $\alpha = 1$ and, when it is parabolic, α is close to 2. For larger or infinity-tending values of α , the profile describes the behavior of a step-index fiber (Figure 1).

$$n(r) = \begin{cases} n_1 \sqrt{1 - 2\Delta \left(\frac{r}{a}\right)^\alpha} & \text{for } r < a \\ n_1 \sqrt{1 - 2\Delta} & \text{for } r > a \end{cases} \quad (7)$$

Figure 1. Index profile for variations of α



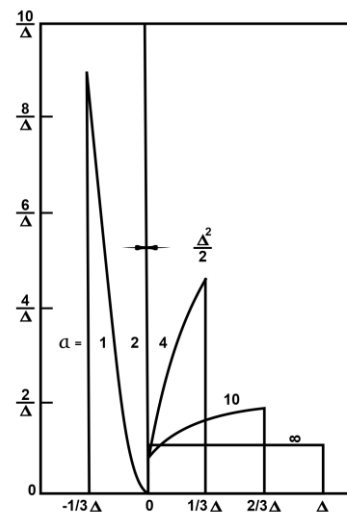
Source: own.

2.1.4. Optimal alpha

It is the condition in which the inferior and superior modes reach time $t = 0$. According to the impulse response (Figure 2) for different profiles with gradual index (other than α) [19].

$$\alpha = 2(1 - \Delta) \quad (8)$$

Figure 2. Relative delay in response to impulse in multimode fibers [19].



Source: own.

2.1.5. Propagation constant for guided modes

A mode exists (propagates) when its propagation constant remains between the value of the core index and the coating index (equation 9). On the other hand, the normalized propagation constant b [20] varies between 0 and 1, in terms of the normalized frequency (equation 1) [16].

Hence:

$$n_2 k < \beta < n_1 k \quad (9)$$

$$b = 1 - \frac{u^2}{V^2} \quad (10)$$

where:

$$u = R \sqrt{k_0 n_1^2 - \beta^2} \quad (11)$$

2.2. Modal dispersion

Modal dispersion (or pulse expansion) is due to the difference in the propagation times of light rays that travel different trajectories in a fiber [18].

$$D = \frac{\Delta T}{L} = \frac{n_1 \Delta}{8c} \left[\frac{s}{m} \right] \quad (13)$$

Source: [19][20]

3. Development of the model

For this work, a spiral dipole with a ground plane that also acts as a reflector was selected, Figure 4, the spiral dipole has an adequate electrical longitude and the wide of the spiral can adjust a good impedance match for the entire range from 2 MHz to 20 MHz.

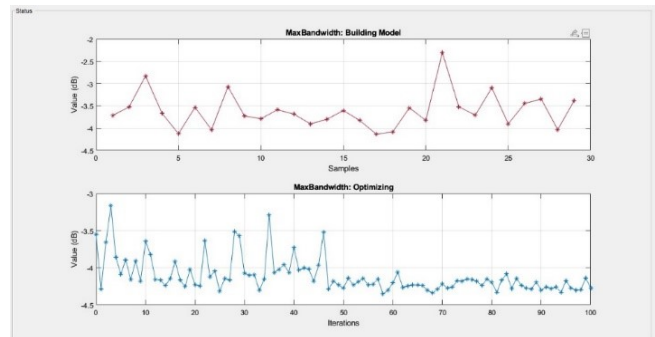
The model proposed in this article involves two equation systems (14 and 15) that depend on the core

refractive index, the parameter α , the core radius, the propagated modes, the wavelength of the fiber, and the constant of the speed of light.

The variables to be optimized were bandwidth and array gain. Although in advance the array assumes low directivity in the lower frequencies of 2 MHz with gains close to 3dBi and a significant improvement in the high 20 MHz being viable to expect values close to 12 dBi.

The resulting values were reached after interaction 47, as can be seen in Figure 3 with subsequent results up to 100 being very similar, although it is not possible to rule out models with better performance values such improvements are not expected to be of importance.

Figure 4. SADEA optimization process numbers, performed in MATALAB.



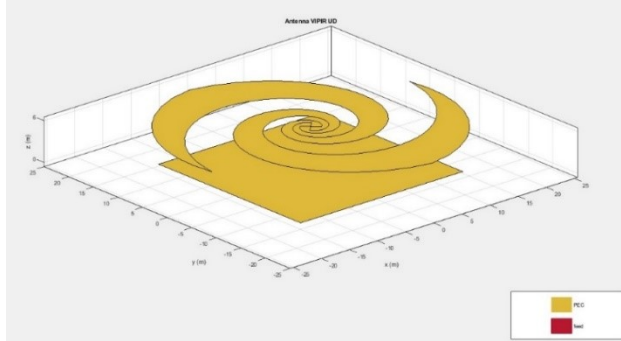
Source: own.

4. Spiral antenna and a reduced ground plane for VIPIR results

From the optimization process, the wide, longitude and other characteristics of the spiral antenna were modified to find the best bandwidth and gain. Since the height of the antenna above the ground plane is related to the gain and directivity in special on lower frequencies, the optimization process always sets the height at the maximum of the available range. In this case 5 m, the spiral design reaches a square of 20 m by

20 m and the spiral arms reach 45 m each one, the general aspect of the design can be seen in Figure 5.

Figure 5: Spiral antenna design for VIVPIR UD obtained on MATLAB.

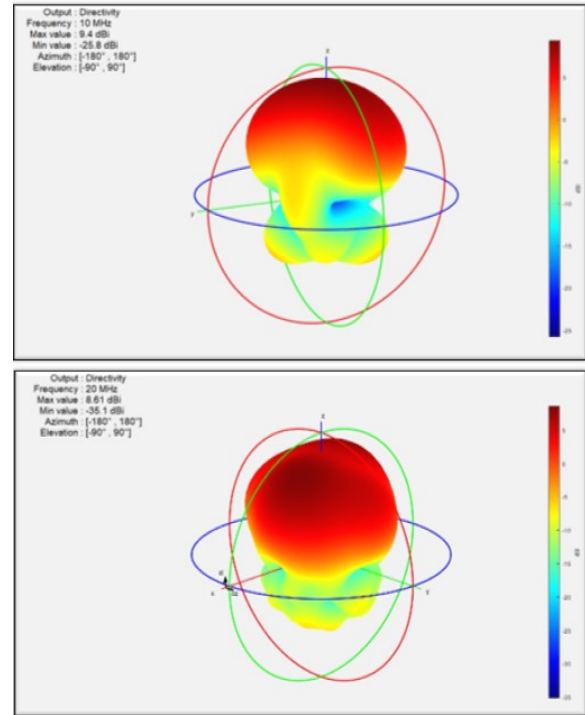
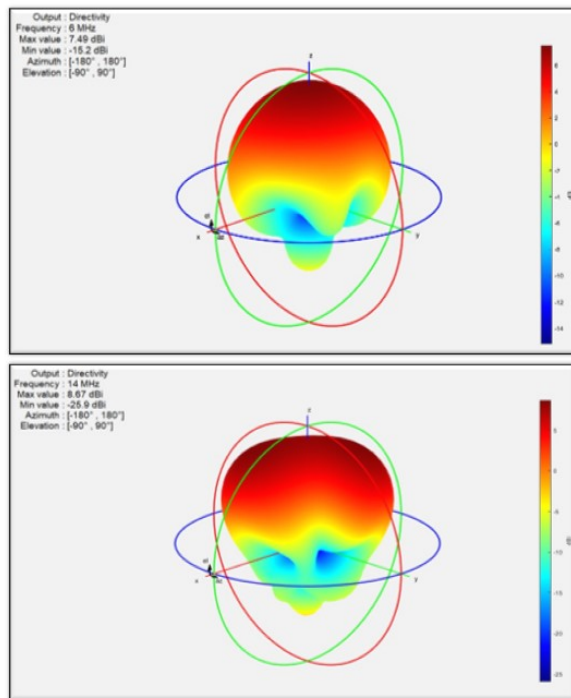


Source: own.

The gain of the design varies from 5 dBi on the lower frequencies 2MHz to 9 dBi at 20 MHz.

Clarifying that in the lower frequencies, the front-to-back ratio is 3dB. A radiation pattern set can be seen in Figure 6.

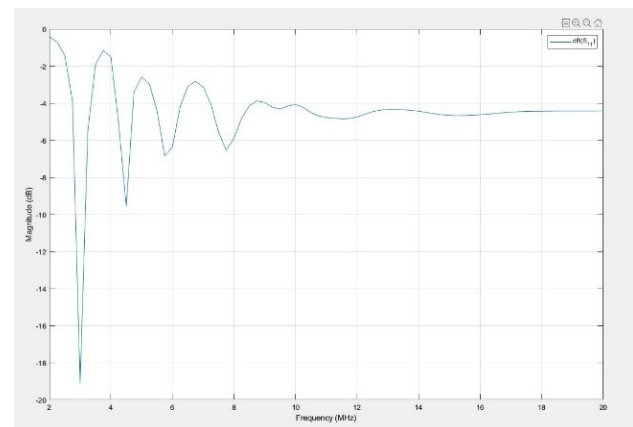
Figure 6: Gain and radiation pattern on 6 MHz of the VIVPIR UD array.



Source: own.

The scattered parameter S11 or reflection parameter behavior can analyze on Figure 7. The design shows performance from 2MHz to 20 MHz, the better the behavior the larger the magnitude of the absorption on dB.

Figure 7. Scattered parameter S11 Vs frequency of the designed VPIR array on MATLAB.



Source: own.

5. Discussion

The obtained antenna design does not effectively cover the entire proposed range, at low frequencies due to the dimensions of the design with wavelength. Although it can operate from 2 MHz its most useful operation is from 3 MHz and can be extended to the entire HF band from 3 to 30 MHz. It was clear from the design that the greater the separation from the ground plane, the better its operation would be in the lower part of the range.[18]

Current and upcoming work with the design proposes ways to improve gain at low frequencies by adding capacitive or inductive loads to extend the electrical length of the spiral arms. What can be achieved with variations in the width of each arm but with the implications of the effect of these loads on the higher frequencies. We are also working on the possibility of using a design for the range of 1 MHz to 5 MHz that complements the one presented here that works very well from 3 to 20 MHz.

The design presented represents a feasible option for the mounting of the ionospheric RADAR VIPIR UD with an infrastructure of lower height above the ground and with operational characteristics like the antenna system traditionally used as a delta antenna for VIPIR systems.

This antenna design results in an innovation for the subject because so far in reviews on the subject we have not had similar proposals in form or performance.

SADEA is an artificial intelligence (AI) tool designed to enhance antenna design methods. It is based on machine learning and evolutionary computation techniques. This approach offers several advantages, including improved optimization quality, greater efficiency, enhanced generality, and increased robustness. SADEA algorithm carries out global optimization and employs a surrogate model built by statistical learning techniques. The method to make

surrogate modeling and optimization work harmoniously is critical in such surrogate model-assisted optimization methods. In SADEA, some ideas of the surrogate model-aware evolutionary search framework are borrowed, see [3] and [4]. SADEA uses differential evolution (DE) as the search engine and Gaussian process (GP) machine learning as the surrogate modeling method applied as AI mechanism to optimize EM design, devices, and conditions, has been developed, and SADEA, as the multi-objective tool is suitable for the synthesis of RADAR antennas.

References

- [1] T. Bullett, R. Livingston, R. Grubb, N. Zabotin, "High Frequency Radars and Ionospheric Sounding with VIPIR," 2020. [Online]. Available: http://lisn.igp.gob.pe/files/first_ionosonde_schol/bullet_HF_sounding.pdf
- [2] T. Bullett, "Dynasonde and VIPIR Ionosonde Field Site Requirements Basic and Research Capabilities," 2018. [Online]. Available: ftp://ftp.ngdc.noaa.gov/ionosonde/documentation/VIPIR/VIPIR_Site_Needs-Sep18.pdf
- [3] T. R. Robinson, "Some analytical results for the propagation and spreading of short electromagnetic pulses in the ionosphere," in IEE Colloquium on Antenna and Propagation Problems of Ultrawideband Radar, pp. 10/1-10/5, 1993.
- [4] C. Wang, M. Zhang, Z. Xu, and C. Chen, "Simulation of ionospheric effects on SAR imaging with noise at P-band," in ISAPE2012, 2012, pp. 419-422. [Online]. Available: <https://doi.org/10.1109/ISAPE.2012.6408795>

- [5] E. Zuccheretti, "Ionospheric radars development," 2010. [Online]. Available: <https://www.earth-prints.org/bitstream/2122/6958/1/Posgrado.pdf>
- [6] T. W. Bullett, N. A. Zabotin, R. C. Livingston, R. N. Grubb, J. E. Mabie, and C. Negrea, "HF radar measurements of the ionosphere using dynasonde methods," in *2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*, 2014. [Online]. Available: <https://doi.org/10.1109/URSIGASS.2014.6929845>
- [7] J. Talukdar, B. Mehta, K. Aggrawal, and M. Kamani, "Implementation of SNR estimation based energy detection on USRP and GNU radio for cognitive radio networks," in *2017 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, 2017, pp. 304-308. [Online]. Available: <https://doi.org/10.1109/WiSPNET.2017.8299767>
- [8] M. Floer, "Design and Implementation of a Software Defined Ionosonde", 2020. [Online]. Available: <https://munin.uit.no/handle/10037/19423>
- [9] B. Isham, "An MF/HF antenna array for ionospheric sounding and measurement of ionospheric radio emissions," in *2013 US National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM)*, 2013. [Online]. Available: <https://doi.org/10.1109/USNC-URSI-NRSM.2013.6525062>
- [10] O. Koloskov, A. Kashcheyev, O. Bogomaz, A. Sopin, B. Gavrylyuk, and A. Zalizovski, "Performance Analysis of a Portable Low-Cost SDR-Based Ionosonde," *Atmosphere (Basel)*, vol. 14, no. 1, p. 159, Jan. 2023. [Online]. Available: <https://doi.org/10.3390/atmos14010159>
- [11] Q. Bai, "Analysis of the particle swarm optimization algorithm", *Computer and Information Science*, vol. 3, no. 1, 2010. [Online]. Available: <https://doi.org/10.5539/cis.v3n1p180>
- [12] P. Rocca, G. Oliveri, and A. Massa, "Differential evolution as applied to electromagnetics," *IEEE Antennas Propag Mag*, vol. 53, no. 1, 2011. [Online]. Available: <https://doi.org/10.1109/MAP.2011.5773566>
- [13] A. Hoorfar, "Evolutionary programming in electromagnetic optimization: A review," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 3, 2007. [Online]. Available: <https://doi.org/10.1109/TAP.2007.891306>
- [14] M. John, M. J. Ammann, "Antenna optimization with a computationally efficient multiobjective evolutionary algorithm," *IEEE Trans Antennas Propag*, vol. 57, no. 1, 2009. [Online]. Available: <https://doi.org/10.1109/TAP.2008.2009775>
- [15] B. Liu, A. Irvine, M. O. Akinsolu, O. Arabi, V. Grout, and N. Ali, "GUI design exploration software for microwave antennas," *J Comput Des Eng*, vol. 4, no. 4, 2017. [Online]. Available: <https://doi.org/10.1016/j.jcde.2017.04.001>
- [16] M. Stein, "Large sample properties of simulations using latin hypercube sampling," *Technometrics*, vol. 29, no. 2, 1987. [Online]. Available: <https://doi.org/10.1080/00401706.1987.10488205>
- [17] B. Liu, H. Aliakbarian, Z. Ma, G. A. Vandenbosch, G. Gielen, "An efficient method for antenna design optimization based on evolutionary

computation and machine learning techniques,”
IEEE Trans Antennas Propag, vol. 62, no. 1,
2014. [Online]. Available:
<https://doi.org/10.1109/TAP.2013.2283605>

[18] Z. Ma, G. A. Vandenbosch, “Low-cost wideband
microstrip arrays with high aperture efficiency,”
IEEE Trans Antennas Propag, vol. 60, no. 6,
2012. [Online]. Available:
<https://doi.org/10.1109/TAP.2012.2194685>