

# Modelling Dispersion Characteristics of Circular Optical Waveguide with Helical Winding– Comparison for Different Pitch Angles

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**Abstract—** In this Article dispersion characteristic of conventional optical waveguide with helical winding at core – cladding interface has been obtained. The model dispersion characteristics of optical waveguide with helical winding at core-cladding interface have been obtained for five different pitch angles. This paper includes dispersion characteristics of optical waveguide with helical winding, and comparison of dispersion characteristics of optical waveguide with helical winding at core-cladding interface for five different pitch angles. Boundary conditions have been used to obtain the dispersion characteristics and these conditions have been utilized to get the model Eigen values equation. From these Eigen value equations dispersion curve are obtained and plotted for modified optical waveguide for particular values of the pitch angle of the winding and the result has been compared.

**KEYWORDS:** Optical fiber communication, fiber dispersion, helical winding, helix pitch angle, modal cutoff.

## I. INTRODUCTION

Optical fibers with helical winding are known as complex optical waveguides. The use of helical winding in optical fibers makes the analysis much accurate [1]. Singh [13] have proposed an analytical study of dispersion characteristics of helically cladded step – index optical fiber with elliptical core. The sheath helix [12] is a cylindrical surface with high conductivity in a preferential direction which winds helically at constant angle around

the core–cladding boundary surfaces. We assume that the waveguide have real constant refractive index of core and cladding is  $n_1$  and  $n_2$  respectively ( $n_1 > n_2$ ).

## II. THEORY AND CALCULATIONS

The optical waveguide is the fundamental element that interconnects the various devices of an optical integrated circuit, just as a metallic strip does in an electrical integrated circuit. The mode theory [10] is used to describe the properties of light that ray theory is unable to explain. A set of guided electromagnetic waves is called the modes [13, 16] of the fiber. For a given mode, a change in wavelength can prevent the mode from propagating along the fiber. The mode is no longer bound to the fiber. The mode is said to be cut off [13]. The wavelength at which a mode ceases to be bound is called the cutoff wavelength [11] for that mode. we consider the following boundary conditions [8].

$$E_{z1} \sin \psi + E_{\phi1} \cos \psi = 0 \quad (1)$$

$$E_{z2} \sin \psi + E_{\phi2} \cos \psi = 0 \quad (2)$$

$$(E_{z1} - E_{z2}) \cos \psi - (E_{\phi1} - E_{\phi2}) \sin \psi = 0 \quad (3)$$

$$(H_{z1} - H_{z2}) \sin \psi + (H_{\phi1} - H_{\phi2}) \cos \psi = 0 \quad (4)$$

The expressions for  $E_z$  and  $H_z$  inside the core are, when ( $r < a$ )

$$E_{z1} = AJ_1(Ua)F(\phi)e^{j(\omega t - \beta z)} \quad (5)$$

$$H_{z1} = BJ_1(Ua)F(\phi)e^{j(\omega t - \beta z)} \quad (6)$$

The expressions for  $E_z$  and  $H_z$  outside the core are, when ( $r > a$ ),

$$E_{z2} = CK_1(Wa)F(\phi)e^{j(\omega t - \beta z)} \quad (7)$$

$$H_{z2} = DK_1(Wa)F(\phi)e^{j(\omega t - \beta z)} \quad (8)$$

where,

$$U^2 = k_1^2 - \beta^2 = \omega^2 \mu \epsilon_1 - \beta^2 \quad (9)$$

$$W^2 = \beta^2 - k_2^2 = \beta^2 - \omega^2 \mu \epsilon_2 \quad (10)$$

The transverse field components can be obtained by using Maxwell's standard relations. So the electric and magnetic field components  $E_\phi$  and  $H_\phi$  can be written as,

Transverse components of the electric and magnetic fields  $E_{\phi 1}$  and  $H_{\phi 1}$  for core region can be written as:

$$E_{\phi 1} = -\left(j/U^2\right)F(\phi)e^{j(\omega t - \beta z)} \left[j(\beta/a)AJ_1(Ua) - \mu\omega UBJ_1'(Ua)\right] \quad (11)$$

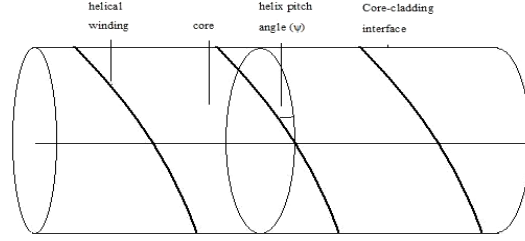
$$H_{\phi 1} = -\left(j/U^2\right)F(\phi)e^{j(\omega t - \beta z)} \left[j(\beta/a)BJ_1(Ua) + \omega\epsilon_1 UAJ_1'(Ua)\right] \quad (12)$$

The axial field components of the electric field and magnetic field  $E_{\phi 2}$  and  $H_{\phi 2}$  for clad region can be written as:

$$E_{\phi 2} = -\left(j/W^2\right)F(\phi)e^{j(\omega t - \beta z)} \left[j(\beta/a)CK_1(Wa) - \mu\omega WDK_1'(Wa)\right] \quad (13)$$

$$H_{\phi 2} = -\left(j/U^2\right)F(\phi)e^{j(\omega t - \beta z)} \left[j(\beta/a)DK_1(Wa) + \omega\epsilon_2 WCK_1'(Wa)\right] \quad (14)$$

We get four equations which involves four unknown constants A, B, C and D.



**Fig. 1** Fiber with conducting helical winding at core cladding interface

$$AJ_v(ua) \left[ \sin \psi + \frac{\beta v}{u^2 a} \cos \psi \right] \quad (15)$$

$$+ BJ_v'(ua) \left[ \frac{j\mu\omega}{u} \right] \cos \psi = 0$$

$$CK_v(wa) \left[ \sin \psi + \frac{\beta v}{w^2 a} \cos \psi \right] \quad (16)$$

$$+ DK_v'(wa) \left[ \frac{j\mu\omega}{w} \right] \cos \psi = 0$$

$$AJ_v(ua) \left[ \cos \psi - \frac{\beta v}{u^2 a} \sin \psi \right] - BJ_v'(ua) \left[ \frac{j\mu\omega}{u} \right] \sin \psi \quad (17)$$

$$- CK_v(wa) \left[ \cos \psi - \frac{\beta v}{w^2 a} \sin \psi \right]$$

$$+ DK_v'(wa) \left[ \frac{j\mu\omega}{w} \right] \sin \psi = 0$$

$$-AJ_v'(ua) \left[ \frac{j\omega\epsilon_1}{u} \right] \cos \psi + BJ_v(ua) \left[ \sin \psi + \frac{\beta v}{u^2 a} \cos \psi \right] \quad (18)$$

$$+ CK_v(wa) \left[ \frac{j\omega\epsilon_2}{w} \right] \cos \psi$$

$$- DK_v(wa) \left[ \sin \psi + \frac{\beta v}{w^2 a} \cos \psi \right] = 0$$

Eq. (15), Eq. (16), Eq. (17) and Eq. (18) will yield a non-trivial solution if the determinant whose elements are the coefficient of these unknown constants is set equal to zero. Thus we have:

$$\Delta = \begin{vmatrix} A1 & A2 & A3 & A4 \\ B1 & B2 & B3 & B4 \\ C1 & C2 & C3 & C4 \\ D1 & D2 & D3 & D4 \end{vmatrix} \quad (19)$$

where,

$$A1 = J_v(ua) \left[ \sin \psi + \frac{\beta v}{u^2 a} \cos \psi \right] \quad (20)$$

$$A2 = J_v'(ua) \left[ \frac{j \mu \omega}{u} \right] \cos \psi$$

$$A3 = A4 = B1 = B2 = 0$$

$$B3 = K_v(wa) \left[ \sin \psi + \frac{\beta v}{w^2 a} \cos \psi \right] \quad (21)$$

$$B4 = K_v'(wa) \left[ \frac{j \mu \omega}{w} \right] \cos \psi$$

$$C1 = J_v(ua) \left[ \cos \psi - \frac{\beta v}{u^2 a} \sin \psi \right] \quad (22)$$

$$C2 = -J_v'(ua) \left[ \frac{j \mu \omega}{u} \right] \sin \psi$$

$$C3 = -K_v(wa) \left[ \cos \psi - \frac{\beta v}{w^2 a} \sin \psi \right]$$

$$C4 = K_v'(wa) \left[ \frac{j \mu \omega}{w} \right] \sin \psi$$

$$D1 = -J_v'(ua) \left[ \frac{j \omega \varepsilon_1}{u} \right] \cos \psi \quad (23)$$

$$D2 = J_v(ua) \left[ \sin \psi + \frac{\beta v}{u^2 a} \cos \psi \right]$$

$$D3 = K_v'(wa) \left[ \frac{j \omega \varepsilon_2}{w} \right] \cos \psi$$

$$D4 = -K_v(wa) \left[ \sin \psi + \frac{\beta v}{w^2 a} \cos \psi \right]$$

After simplifying the determinant, we get a simplified equation for lowest order modes.

$$U \frac{J_1(Ua)}{J_1(Ua)} \left( \sin \psi + \frac{\beta}{U^2 a} \cos \psi \right)^2 - \frac{k_1^2 J_1(Ua)}{U J_1(Ua)} \cos^2 \psi \quad (24)$$

$$- W \frac{K_1(Wa)}{K_1(Wa)} \left( \sin \psi + \frac{\beta}{W^2 a} \cos \psi \right)^2 + \frac{k_2^2 K_1(Wa)}{W K_1(Wa)} \cos^2 \psi = 0$$

### III. RESULTS

It is now possible to interpret the characteristic equation (Eq. 24) in numerical terms. This will give us an insight into model properties of our waveguide. For this we can use following relations,

$$U \frac{J_1(Ua)}{J_1(Ua)} \left( \sin \psi + \frac{\beta}{U^2 a} \cos \psi \right)^2 - \frac{k_1^2 J_1(Ua)}{U J_1(Ua)} \cos^2 \psi \quad (25)$$

$$- W \frac{K_1(Wa)}{K_1(Wa)} \left( \sin \psi + \frac{\beta}{W^2 a} \cos \psi \right)^2 + \frac{k_2^2 K_1(Wa)}{W K_1(Wa)} \cos^2 \psi = 0$$

$$b = \left( \frac{aw}{V} \right)^2 = \left( \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2} \right) \quad (26)$$

$$V^2 = (u^2 + w^2) a^2 = \left( \frac{2\pi a}{\lambda} \right)^2 (n_1^2 - n_2^2) \quad (27)$$

where  $b$  and  $V$  are known as normalization propagation constant and normalized frequency parameter respectively. We make some simple calculations based. We choose  $n_1=1.50$ ,  $n_2=1.46$  and  $\lambda=1.55\mu\text{m}$ .

#### A. Dispersion Curve

##### 1. Dispersion Curve for Pitch Angle $\psi=0^\circ$

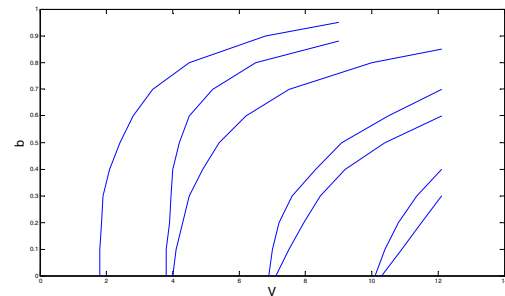


Fig. 2 Dispersion curve for pitch angle  $\psi=0^\circ$

##### 2. Dispersion Curve for Pitch angle $\psi=30^\circ$

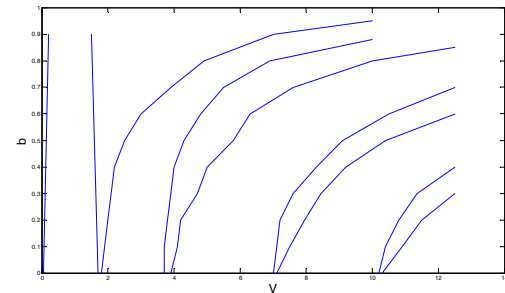


Fig. 3 Dispersion curve for pitch angle  $\psi=30^\circ$

### 3. Dispersion Curve for Pitch Angle $\psi=45^\circ$

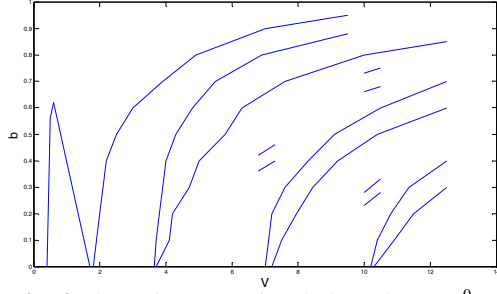


Fig. 4 Dispersion curve for pitch angle  $\psi=45^\circ$

### 4. Dispersion Curve for Pitch Angle $\psi=60^\circ$

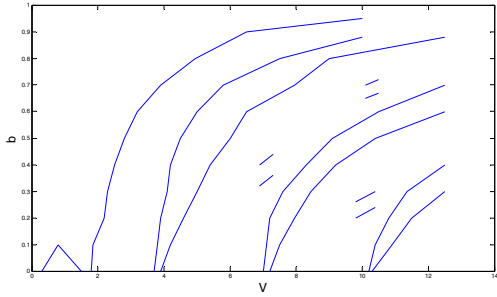


Fig. 5 Dispersion curve for pitch angle  $\psi=60^\circ$

### 5. Dispersion Curve for Pitch Angle $\psi=90^\circ$

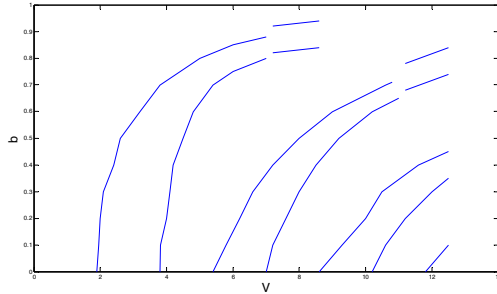


Fig. 6 Dispersion curve for pitch angle  $\psi=90^\circ$

We observed that, they all have standard expected shape. This effect is undesirable for the possible use of. This means that one effect of conducting helical winding is to these waveguide for long distance communication in pairs that is cutoff values for two adjacent modes converge.

We found that some curves have band gaps of discontinuities between some value of  $V$ . These represent the band gaps or forbidden bands of the structure. These are induced by the periodicity of the helical windings.

### B. Dependence of Cutoff Values on Pitch Angle

From Table I, we note particularly that the dependence of the cutoff  $V$ -value ( $V_c$ ) on  $\psi$  is such that as  $\psi$  is increased, there is a drastic fall in  $V_c$  at  $\psi=30^\circ$ , and then a small increase as  $\psi$  goes from  $30^\circ$  to  $60^\circ$ ; then there is a quick rise as  $\psi$  changes from  $60^\circ$  to  $90^\circ$  (Fig. 7).

Thus the two most sensitive regions in respect of the influence of helical pitch angle  $\psi$  on the cutoff values and the model properties of waveguides are ranges from  $\psi=0^\circ$  to  $\psi=30^\circ$  and  $\psi=60^\circ$  to  $\psi=90^\circ$  and these ranges of pitch angle expected to have potential applications with  $\psi$  as a means for controlling the model properties split the modes and remove a degeneracy which is hidden in conventional waveguide without windings.

TABLE I CUTOFF  $V_c$  VALUES FOR SOME LOWER ORDER MODES

<i>Pitch Angle <math>\Psi</math> (<math>^{\circ}</math>)</i>	<b>0</b>	<b>30</b>	<b>45</b>	<b>60</b>	<b>90</b>
<i>Cutoff Normalized Frequency <math>V_c</math></i>	1.80	0.05	0.40	0.30	1.90
	3.80	1.70	1.70	1.50	3.80
	4.00	1.80	1.80	1.80	5.40
	6.90	3.70	3.65	3.70	7.00
	7.10	3.90	3.70	3.90	8.60
	10.10	7.00	7.00	7.00	10.20
	10.30	7.10	7.20	7.20	11.80
	-	10.20	10.20	10.20	-
	-	10.30	10.30	10.30	-

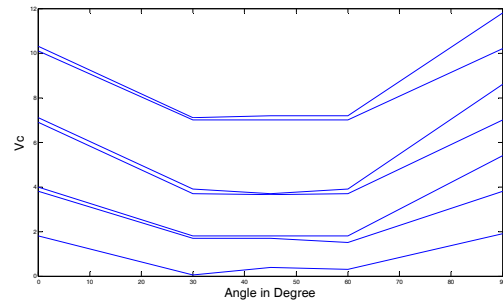


Fig. 7 Dependence of cutoff values  $V_c$  on the pitch angle  $\psi$

## IV. CONCLUSION

We observed that, they all have standard expected shape, but except for lower order modes they comes in pairs, that is cutoff values for two adjacent mode converge. This

means that one effect of conducting helical winding is to split the modes and remove a degeneracy which is hidden in conventional waveguide without windings.

From the above discussions we can conclude that the modal cutoff for helical pitch angle  $\psi=30^\circ$ ,  $45^\circ$  and  $60^\circ$  are higher than the modal cutoff for helical pitch angle  $\psi=0^\circ$  and  $90^\circ$ . This means, for some specific range of cutoff values  $V_c$ , one can have greater number of modes for helical pitch angle  $\psi=30^\circ$ ,  $45^\circ$  and  $60^\circ$  than for helical pitch angle  $\psi=0^\circ$  and  $90^\circ$ . So the helical pitch angle  $\psi=30^\circ$ ,  $45^\circ$  and  $60^\circ$  are better than helical pitch angle  $\psi=0^\circ$  and  $90^\circ$ .

## REFERENCES

- [1] D. Kumar, and O.N. Singh II, "Modal characteristics equation and dispersion curves for an elliptical step-index fiber with a conducting helical winding on the core-cladding boundary - An analytical study," IEEE, J. Lightwave Technol. Vol. 20, pp. 1416-1424, 2002.
- [2] D.A. Watkins, *Topics in Electromagnetic Theory*, John Wiley and Sons Inc., NY, 1958.
- [3] V.N. Mishra, V. Singh, B. Prasad, and S.P. Ojha, "Optical Dispersion curves of two metal-clad light guides having double convex lens core cross sections," Microwave Opt. Technol. Lett. Vol. 24, pp. 229-232, 2000.
- [4] V.N. Mishra, V. Singh, B. Prasad, and S.P. Ojha, "An Analytical investigation of dispersion characteristic of a light guide with an annular core cross section bounded by two cardioids," Microwave Opt. Technol. Lett., Vol. 24, pp. 229-232, 2000 and Microwave Opt. Technol. Lett., Vol. 16, pp. 213-221, 1999.
- [5] V. Singh, S.P. Ojha, B. Prasad, and L.K. Singh, "Optical and microwave Dispersion curves of an optical waveguide with a guiding region having a core cross section with a lunar shape," Optik, Vol. 110, pp. 267-270, 1999.
- [6] V. Singh, S.P. Ojha, and L.K. Singh, "Model Behavior, cutoff condition, and dispersion characteristics of an optical waveguide with a core cross section bounded by two spirals," Microwave Opt. Technol. Lett. Vol. 21, pp. 121-124, 1999.
- [7] V. Singh, S.P. Ojha, and B. Prasad, "Weak guidance modal dispersion characteristics of an optical waveguide having core with sinusoidally varying gear shaped cross section," Microwave Opt. Technol. Lett. Vol. 22, pp. 129-133, 1999.
- [8] D. Gloge, "Dispersion in weakly guiding fibers," Appl. Opt. Vol. 10, pp. 2442-2445, 1971.
- [9] P.K. Choudhury, D. Kumar, Z. Yusoff, and F.A. Rahman, "An analytical investigation of four-layer dielectric optical fibers with an nano-coating - A comparison with three-layer optical fibers," PIER Vol. 90, pp. 269-286, 2009.
- [10] G. Keiser, *Optical Fiber Communications*, Chap. 2, 3rd ed. McGraw-Hill, Singapore, 2000.
- [11] J. Ming-Liu, *Photonic Devices*, Cambridge University Press, UK, 2005.
- [12] D. Kumar and O.N. Singh II, "Towards the dispersion relations for dielectric optical fibers with helical windings under slow and fast wave considerations - a comparative analysis," PIER, Vol. 80, pp. 409-420, 2008.
- [13] D. Kumar and O.N. Singh II, "An analytical study of the modal characteristics of annular step-index fiber of elliptical cross-section with two conducting helical windings on the two boundary surfaces between the guiding and non-guiding regions," Optik, Vol. 113, pp. 193-196, 2002.
- [14] U.N. Singh, O.N. Singh II, P. Khastgir, and K. K. Dey "Dispersion characteristics of helically cladded step - index optical fiber analytical study," J. Opt. Soc. Am. B, Vol. 12, pp. 1273-1278, 1995.
- [15] M.P.S. Rao, V. Singh, B. Prasad, and S.P. Ojha "Model characteristic and dispersion curves of hypocycloidal optical waveguide," Optik, Vol. 110, pp. 81-85, 1999.
- [16] A. Ghatak and K. Thyagarajan, *Optical Electronics*, Cambridge University Press, India, 2008.
- [17] D. Kumar and O.N. Singh II, "Some special cases of propagation characteristics of an elliptical step-index fiber with a conducting helical winding on the core-cladding

boundary – An analytical treatment,” *Optik* Vol. 112, pp. 561-566, 2001.

- [18] G. P. Agrawal, *Fiber Optic Communication Systems*, 3rd ed. John Wiley and Sons, Inc., New York, 2002.



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