Mode analysis of spherical probe of fiber sensor for smart grids

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Abstract. Fiber sense technologies of vibration, ultrasonic, and partial discharge are the core technologies for building smart grids. Single-mode fiber probes are key components of the above fiber sensors. The evolution of optical wave modes in fiber probes directly affects performance of fiber sensor. A simulation model for single-mode fiber spherical probe is established, and the modes of the spherical probe are simulated and analyzed in detail, and the evolution law of the optical wave mode in spherical probe is explored. The simulation results show that the longitudinal non-uniform spherical probe structure excites high-order modes. The fundamental mode power is gradually reduced, and the high-order mode power increases continuously. The main mode coupling in a single-mode fiber spherical probe is a strong coupling between the first and second-order cladding modes. At the top of the single-mode fiber spherical probe, with the decrease of the core layer radius, the high-order guided mode gradually transforms into the radiation mode, and the number of transmitted guided modes decreases gradually.

1. Introduction

Through the measurement of physical quantities such as vibration, ultrasonic, and partial discharge, the mechanical failure and insulation state of the equipment can be monitored. The existing monitoring methods are mainly electronic sensors, such as piezoelectric ceramics, pulse current, ultra-high frequency, ultrasonic detection and so on, which are susceptible to electromagnetic interference. Therefore, in the local power supply and long-distance information transmission and
other aspects, there are more use restrictions [1, 2]. Fiber sensors have the characteristics of anti-electromagnetic interference, corrosion resistance, electrical insulation, small volume, light weight, high sensitivity and low cost [3]. The application of optical fiber vibration sensors have been reported in power systems, including operational status monitoring and fault diagnosis of transformers and generators, motor, transmission line, and so on[4-6]. Fiber sense technologies of vibration, ultrasonic, and partial discharge are the core technologies for building smart grids. Single-mode fiber probes are key components of the above fiber optic sensors.

A simple mechanism useful to tailor the field profile in single mode fibers is proposed [7]. Preparation technique of optical fiber’s sphere-end is introduced [8]. Based on light ray theory and equivalent lens method, the effect of multiple mode optical fiber with sphere-end is analyzed. Test results about coupling efficiency between two multiple mode fibers which have different end are given.

The evolution of optical wave modes in fiber probes directly affects the performance of fiber sensor. The mode analysis of single-mode fiber spherical probes has not been reported. A simulation model for single-mode fiber spherical probe is established, and the mode of the spherical probe is simulated and analyzed in detail, and the evolution law of the light wave mode in spherical probe is explored.

2. Theoretical modeling

![Figure 1. Geometric structure of single-mode fiber spherical probe](image)

The sensing head of the fiber sensor includes a fiber spherical probe and a sensitive area, as shown in figure 1. The geometrical model of spherical probe with single-mode fiber was established by local amplification of the tip of the probe. The AA' plane is the initial plane, and its structure is exactly the same as the cross section structure of the single-mode fiber. The B (B') point is the vertex of the spherical probe. The shadow CC' plane is any cross section of the probe, and its structure is determined by the position of the section. The core radius and cladding radius on the AA' plane are equal to the core and cladding radius of the single-mode fiber, respectively, denoted a₀, b₀. The CC' face has a core radius of a and a cladding radius of b. In the axial direction of the probe, the distance between the arbitrary cross section CC' and the initial plane is denoted by Z, and the distance between the initial plane AA' and the equivalent spherical center O is denoted by Z₀. The thickness of the probe
is denoted by T. According to the geometric relationship,

\[ Z_0 = \sqrt{R^2 - b_0^2} \]  

(1)

\[ T = R - Z_0 = R - \sqrt{R^2 - b_0^2} \]  

(2)

The closer it is to the tip of the probe, the smaller the cladding radius \( b \) is. After reaching a certain interface, the core of the probe is exposed to air, and the cross-section of CC' is changed from the former core-clad structure to a single core-layer structure. The axial coordinate \( Z_i \) of the interface distance from the initial surface AA' can be expressed as:

\[ Z_i = \sqrt{R^2 - a_0^2} - Z_0 = \sqrt{R^2 - a_0^2} - \sqrt{R^2 - b_0^2} \]  

(3)

When \( Z \) is less than \( Z_i \), the probe and the air environment form a three-layer structure (region I), and when \( Z \) is greater than or equal to \( Z_i \) and less than or equal to the probe thickness \( T \), the probe and the air environment form a two-layer structure (region II). The relationship between the structural parameters \( a, b \) and the axial coordinate \( Z \) of any section in the two regions is as follows.

\[
\begin{align*}
  &a = a_0 \\
  b = \sqrt{R^2 - (Z + \sqrt{R^2 - b_0^2})^2} & (0 \leq Z < Z_i) \\
  &a = \sqrt{R^2 - (Z + \sqrt{R^2 - b_0^2})^2} \\
  b = a & (Z_i \leq Z \leq T)
\end{align*}
\]  

(4)

Taking corning smf-28 single mode fiber as reference, the core refractive index of spherical probe \( n_1 \) is 1.45205, and the cladding refractive index \( n_2 \) is 1.44681, and the refractive index \( n_0 \) of air is 1. The working wavelength is 1550 nm. The core radius \( a_0 \) of the initial surface of the probe is 4 \( \mu \)m, and the cladding radius \( b_0 \) is 62.5 \( \mu \)m. The radius of curvature of the spherical probe \( R \) is 250 \( \mu \)m.

3. Simulation results and analysis

3.1. optical wave mode in single-mode fiber spherical probe

Based on the improved eigen mode expansion method [9], the evolution of modes and their transmission process in single-mode fiber spherical probes are simulated and analyzed in detail.

Figure 2 shows the variation curves of the effective refractive index of the main modes with the axial coordinate \( z \) in the spherical probe. The effective refractive index of the fundamental mode in region I remains substantially constant. The effective refractive index of higher order modes in region I is all larger than that of air, which decreases with the decrease of the cladding radius of spherical probe. The effective refractive index of higher order modes are pairwise approximate equality and the variation is consistent. The odd order mode and the adjacent even order mode can be regarded as a group of modes. When the cladding mode is transmitted to the top of the core exposed probe, because the effective refractive index of the mode is greater than that of the air, the cladding mode in the region
I will be converted to the higher-order guided mode of the region II, and the spherical probe in the region II is a multimode waveguide. The effective refractive index of all modes in the region II, including the fundamental mode, decreases rapidly with the decrease of the core radius of the probe. When the effective refractive index of the mode is reduced to less than 1.0, the higher-order guided mode is converted to a radiative mode, and the number of guided modes can be gradually reduced, and the power leakage occurs.

Figure 2. The effective refractive index of the main modes of spherical probe

Figure 3 shows the variation curves of the main mode normalized power with the axial coordinate z in a single-mode fiber spherical probe. From Fig. 3, it can be seen that the fundamental mode power decreases slightly near the interface $z_i$ in the region I and decreases greatly in the region II, corresponding to the increasing trend of the higher order mode power as a whole. With the change of the structure of the spherical probe, the first-order mode (mode2) and the second-order mode (mode3) are strongly coupled during the evolution process. Before the mode coupling, the effective refractive index of the two modes is approximately equal, the close effective refractive index determines the strong interaction between the modes, the mode power is obviously exchanged, and most of the first-order modes transmit to the second-order modes. After that, the difference of effective refractive index between the first and second order cladding modes increases gradually, and the interaction between the two modes weakens, and they remain relatively independent.

Figure 3. The normalized power of the main modes of spherical probe
3.2. Evolution of Mode Field in Single-Mode Fiber spherical probe

The segmentation section before and after the coupling position of the first-order and second-order cladding modes is selected as the observation surface. The evolution law of the mode field is shown in Fig. 4.

![Evolution of (a) first-order and (b) second-order cladding mode field distribution](image)

**Figure 4.** Evolution of (a) first-order and (b) second-order cladding mode field distribution

From fig. 4, it is shown that the effective refractive index of the first-order cladding mode in the spherical probe is the closest to the fundamental mode, and the field distribution of the mode can be regarded as the superposition of the quasi-fundamental mode field along the radial distribution of the Gaussian distribution in the core layer and the annular distribution in the cladding layer. The power of the first-order cladding mode is mainly concentrated in the core layer, and the power transmitted through the cladding layer is less. Correspondingly, the power of the second-order cladding mode is completely distributed in the cladding layer, and the field is a single ring. With the decrease of the radius of the spherical probe cladding, the power of the two modes appears peak and valley values along the circumference, which shows that the field gradually splits into two symmetrical lobes in the x and y directions. In the vicinity of the coupling position of the mode, the power in the core layer of the first-order cladding mode is gradually transferred to the cladding layer, and the change of the power distribution of the second-order cladding mode is opposite.

4. Conclusion

The evolution of optical mode of single-mode fiber spherical probe is simulated and analyzed. The change of effective refractive index and normalized power of spherical probe is analyzed. The longitudinal nonuniform spherical probe structure excites higher-order modes, and the fundamental mode power is gradually reduced, and the high-order mode power increases continuously. The effective refractive index of higher order modes are pairwise approximate equality and the variation is consistent. The odd order mode and the adjacent even order mode can be regarded as a group of modes. The main mode coupling in a single-mode fiber spherical probe is a strong coupling between the first and second-order cladding modes. The effective refractive index of the two modes is gradually approaching during the evolution process, and the first-order cladding mode transmits most of the power to the second-order cladding mode. At the top of the single-mode fiber spherical probe, with the decrease of the core layer radius, the high-order guided mode gradually transforms into the radiation mode, and the number of transmitted guided modes decreases gradually, and the power leakage occurs. The conclusions can provide a theoretical reference for the fiber sensing technology of building a
smart grid.

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