Description of Important Parameters for Ytterbium-Doped Silica Optical Fiber

The design of optical fiber waveguide structures is based on the principle of total internal reflection. These structures can be characterised by optical fiber parameters.The refractive index and cross-sectional shape of optical fiber waveguides can be designed through ions codoping. The manufacturing process of optical fiber consists of two main steps: Preparation of fiber preforms and fiber drawing. The fiber preforms act as a 'precursor' for the fiber, which is drawn into an optical fiber with appropriate size.

Total internal reflection of Laser requires that the optical fiber structure must meet the following conditions: the laser must be emitted from a dense medium into a sparse medium, and the incident angle must satisfy the Fresnel condition. In optical fiber design, the waveguide's refractive index distribution can be achieved through ions co-doping, and the angle condition can be characterised by the fiber's corresponding physical parameters.

Taking ytterbium doped double clad fiber as an example, the basic structure of the optical fiber waveguide is shown in Figure 1. The light-guiding region consists of three parts: the core; the inner cladding; and the outer cladding. Assuming their respective refractive indices are n_1, n_2 and n_3, respectively. To ensure that the laser propagates in the fiber core without leaking to the cladding, $n_1 > n_2$ must be satisfied. Similarly, in order to confine the pump light within the cladding, the refractive index of the inner cladding must be bigger than that of the outer cladding (i.e. $n_2 > n_3$).

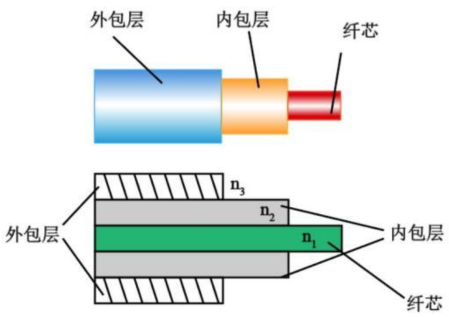

Figure 1 Basic structure of double clad fiber

In order to create a profile structure with a refractive index that decreases gradually from the core to both sides, it is necessary to regulate the refractive index by doping different ions in different regions. In addition to Yb3+, the ions doped in optical fibers also include co doped ions such as phosphorus (P), aluminum (Al), germanium (Ge), and fluorine (F).These co doped components can not only regulate the refractive index, but also improve the quartz matrix and activate ion luminescence. Although the type and concentration of co doped ions can have different effects on the refractive index of waveguides, introducing them does not significantly alter the additional loss of quartz-based fibers, which is the basic condition for the usability of optical fibers. Therefore, in optical fiber design, it is necessary to arrange the doping situation of each region reasonably to simultaneously consider the waveguide structure and laser properties.

The efficiency of a laser is influenced not only by the doped ions, but also by the shape of the inner cladding. The shape of the inner cladding primarily affects the absorption of pump light. The more circularly symmetric the waveguide structure, the fewer times the pump light passes through the core region, resulting in lower pump conversion efficiency. To prevent the pump light from escaping in a spiral pattern, the inner cladding is usually designed to be asymmetric, with shapes such as hexagonal, octagonal or D-shaped being the most common. This significantly enhances the fiber's absorption by breaking the circular symmetry of the fiber waveguide.

In addition to the shape of the cladding, other physical parameters of the fiber can also characterize its performance. More important fiber parameters include numerical aperture, normalized frequency, mode field diameter, etc.

Numerical aperture is a parameter used to characterize the ability of optical fibers to confine light. The larger the numerical aperture, the larger the laser aperture angle that can be transmitted, and the stronger the ability to confine light. For the double clad fiber structure shown in Figure 1, the numerical aperture (NA) is defined as:

$$NAcore = \sqrt{n_1^2 - n_2^2}$$

$$NAclad = \sqrt{n_2^2 - n_3^2}$$

The numerical aperture (NA) values for the core and cladding are denoted as NAcore and NAClad, respectively. Meanwhile, n1, n2 and n3 represent the refractive indices of the core, inner cladding and outer cladding, respectively. The NA of the core can be used to estimate the number of propagation modes (guided modes), and the NA of the cladding can be used to evaluate the pumping coupling efficiency. For standard single-mode fibers, NAcore is typically 0.14, with a core diameter of 6–10 μm. In large-core fibres, NA is usually designed to be lower in order to control beam quality.

For a given optical fiber, the number of guided modes is determined. The number of guided modes is related to core diameter size, refractive index, and signal wavelength of the optical fiber, and is usually characterized by the normalized frequency V. The definition of the V parameter is as follows:

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{\pi d}{\lambda} NA_{core}$$

In the formula, a is the core radius, d is the core diameter, and λ is the signal wavelength. The larger the V value, the greater the number of modes that the optical fiber can accommodate. For typical step - index optical fibers, when the V value is less than 2.405, it is a single-mode optical fiber; For multi-mode opticalfibers, the number of guided modes can be estimated using $V^2/2$.

The parameter reflecting the mode distribution is the effective mode field diameter (MFD), defined as the diameter of the region occupied by the mode when the field strength distribution decays to 1/e of its maximum value. The effective MFD is of great significance for calculating the laser power density in optical fibers. The calculation method for MFD is as follows:

$$deff = \frac{2\sqrt{2}\int E_i^2 r dr}{[\int E_i^4 r dr]^{\frac{1}{2}}}$$

Ei is the mode field intensity distribution of the i-th mode. when designing optical fibers, the above parameters need to be considered When conducting preliminary screening of the manufactured optical fibres, the shape and physical dimensions of the optical fiber end face also need to be taken into account.