Optik 142 (2017) 497–508

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Theoretical analysis on nonlinearity of optical fiber with uniaxial crystal material cladding

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ARTICLE INFO

Article history:
Received 23 February 2017
Accepted 31 May 2017

PACS:
42.81.Qb
42.81.Dp
07.60.Vg

Keywords:
Nonlinearity
Fiber
Uniaxial crystal
Telecommunication

ABSTRACT

The effective mode area and nonlinearity of a proposed fiber with cladding made of uniaxial anisotropic crystal material are derived by fully vectorial method, the influence of k_{cl}, the ratio of the extraordinary to the ordinary ray index, on optical field distribution and nonlinear coefficient γ is investigated theoretically. The results indicate that k_{cl} has no impact on optical field distribution and nonlinearity at the wavelength of near 1330 nm (crossing point of the curves), but at short wavelength of below 1330 nm, the larger k_{cl} is, the more scattering the optical mode field is. However, at the long wavelength, the conclusion is just contrary and k_{cl} has more obvious impact on optical field distribution and nonlinearity than that at short wavelength. Thus the nonlinearity γ can be effectively modified by tailoring k_{cl} at given other parameters of the fibers, and these results provide basis theory for designing optical communication components and optical sensors.

1. Introduction

Besides dispersion and loss of fiber, fiber nonlinearity plays an important role in high-bit-rate and large capacity long-haul optical communication system. Nonlinear effects occurring inside optical fibers, such as self-phase modulation(SPM), cross-phase modulation(XPM) [1], four-wave mixing (FWM) [2], stimulated scattering and etc, can severely limit the power of multichannel lightwave systems and also leads to pulse distortion and low SNR. At the same time, it can be useful for making fiber-based Brillouin components or sensors [3]. In general, it is desirable to minimize the nonlinear effect as much as possible to ensure the transmission quality of optical signals in optical communication systems. On the other hand, fiber nonlinearities attract considerably more attention because of their potential applications in fiber-optic devices, such as fiber lasers, amplifiers and sensors [4]. Meanwhile, parametric processes can be applied to tunable wavelength conversion and parametric oscillators [5], highly nonlinear fiber (HNLF) can be employed for pulse compression [6,7]. Fiber nonlinearities depend on optical parameters and fiber geometrical properties, so that nonlinearity can be tailored by optimizing fiber design. For instance, large effective mode area fibers, i.e., low nonlinearity fibers are extremely potential for large capacity and long-haul transmission system and laser applications [8], while highly nonlinear fibers can be used for wavelength tuning of mode-locked lasers and supercontinum generation [9].

It is well known that transmission characteristics of optical pulse, such as attenuation, dispersion and nonlinearity, basically depend on the refractive index distribution of optical fibers [10,11]. Anisotropic crystal material has complex index

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http://dx.doi.org/10.1016/j.ijleo.2017.05.111

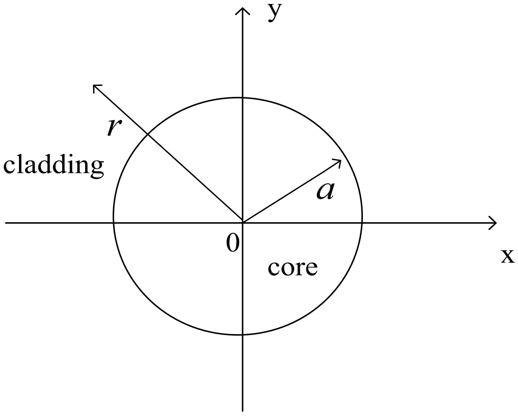

Fig. 1. Profile of a fiber with cladding made of uniaxial crystal materials.

distribution, and uniaxial crystal material has the simplest index distribution among other anisotropic crystal materials. Fibers with either core or cladding made of uniaxial anisotropic crystal have been investigated since the early 1970s. Transmission characteristics and cut-off condition of fiber with a uniaxial crystal core were investigated and the corresponding fiber has been commercialized [12,13]. A W-profile doubly clad fiber with an inner cladding made of a uniaxial crystal material was proposed and the studied results indicate that the zero-dispersion can be effectively adjusted through tailoring the ratio of the extraordinary to the ordinary ray index [14], and polarization characteristics of this kind of fibers are different from the conventional fibers [15]. Wakari M et al. [16] experimentally investigated the fiber polarizer with cladding made of birefringence crystal material. The reflectivity of the fiber Bragg grating with uniaxial crystal material cladding was analyzed and results admit that the ratio of the extraordinary to the ordinary ray index has strong impact on its reflective spectrum [17,18]. Fiber-based devices made of anisotropic crystal have been explored for various applications. But to the best of our knowledge, the effective mode area and nonlinearity of a fiber with cladding made of uniaxial anisotropic crystal material was not presented before.

In this work, the expressions of effective mode area and nonlinearity of the fiber with cladding made of uniaxial anisotropic crystal material are derived by fully vectorial method, and simulation curves of optical field distribution and nonlinearity varying with index of cladding are obtained. The results indicate that the refractive index distribution of uniaxial anisotropic crystal has obvious impacts both on optical field distribution and nonlinearity of this kind of fibers. The magnitude and characteristics of these impacts depend on the value of the ratio of the extraordinary to the ordinary ray index. These results provide a new method to effectively modify nonlinearity by tailoring the index distribution without changing the other parameters of the fibers and also provides a basis theory for designing optical communication devices.

2. Theory

2.1. The characteristic equation

The sketch of the fiber with cladding made of uniaxial crystal material was illustrated in Fig. 1. Note that a is the core radius, n_0 is the core refractive index. The cladding with an infinite diameter is made of uniaxial crystal material whose optical axis is taken to be parallel to the axis of the fiber, i.e. z-axis, and its principal axis indices are n_x, n_y and n_z respectively, which satisfy $n_x = n_y \neq n_z$. The axial electric and magnetic field components satisfy wave equation as follows [19]

$$\begin{cases} \left(\nabla_t^2 + k_0^2 n_0^2 - \beta^2\right) E_z = 0 \\ \left(\nabla_t^2 + k_0^2 n_0^2 - \beta^2\right) H_z = 0 \end{cases} \quad r < a \tag{1}$$

$$\begin{cases} \left(\nabla_t^2 + k_0^2 n_z^2 - k_{cl}^2 \beta^2\right) E_z = 0 \\ \left(\nabla_t^2 + k_0^2 n_t^2 - \beta^2\right) H_z = 0 \end{cases} \quad r > a \tag{2}$$

where k_0 is the wave number in vacuum, β is the propagation constant. If $\beta < kn_0$, the parameters are defined as

$$k_{cl} = \frac{n_z}{n_t},\ \Delta = \frac{n_0 - n_t}{n_0},\ \mathrm{U} = \mathrm{a}\sqrt{k^2 n_0^2 - \beta^2},\ \mathrm{W} = \mathrm{a}\sqrt{\beta^2 - k^2 n_t^2},\ \mathrm{V} = \mathrm{ak}\sqrt{n_0^2 - n_t^2},$$