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Evolution of transmission spectra of double cladding fiber during etching

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ABSTRACT

We investigate the evolution of optical transmission through a double cladding fiber-optic structure during etching. The structure is formed by a section of SM630 fiber with inner depressed cladding between standard SMF-28 fibers. Its transmission spectrum exhibits two resonance dips at wavelengths where two cladding modes have almost equal propagation constants. We measure transmission spectra with decreasing thickness of the cladding and show that the resonance dips shift to shorter wavelengths, while new dips of lower order modes appear from long wavelength side. We calculate propagation constants of cladding modes and resonance wavelengths, which we compare with the experiment.

1. Introduction

Fiber-optic structures based on interaction and transformation between fundamental core mode and higher-order modes, in particular cladding modes, are intensively studied for applications in fiber sensing technologies and telecommunication. Cladding modes are inherent to optical fiber; however, the fiber structure should be modified in some way to couple light to these modes from the core mode. Different defects of optical fiber have been used for the excitation of cladding modes: splice of dissimilar fibers [1,2], displaced splice [3], taper [4], bubble [5], collapsed air holes [6,7], gratings [3], and others. Properties of cladding modes depend strongly on the type of the fiber; therefore, propagation of cladding modes in different types of fibers has been considered: standard [8], double cladding [1], triple cladding [9], microstructured (photonic crystal) [7,10], thinned core [11] and multimode. In addition, cladding modes can be controlled by fiber etching [12], tapering [13], coating with an overlay of transparent material [13,14] or absorber [15].

A combination of two defects can be made in the fiber to create an interferometer-like structure [5,16,17]. Such a structure with two defects can be formed when a section of nonstandard fiber is spliced between normal fibers [1,18]. Other combinations can be created: two tapers [8,19–21], displaced splice and mirror, two pairs of splices, double cladding and multimode fibers [22], long-period fiber grating with misaligned splice [3], and others.

Since cladding modes are involved in transmission of light through the fiber structure, these interferometers are highly sensitive to physical parameters of the fiber and the external medium. The sensitivity to the external medium is due to the fact that the cladding modes, in contrast to the core mode, have evanescent field propagating outside of the fiber cladding. Therefore, such fiber structures are used to create sensors of refractive index [4,7,11,17,20], temperature [9,22], bending [23], pH value [14], vibration [19], humidity [12], and for simultaneous measurement of these parameters [21].

Similar fiber structures that couple the core mode and the cladding modes are long-period fiber gratings, which are formed by periodical perturbation along the fiber with period of about hundreds of microns [24,25]. It has been shown that the resonance wavelengths of long-period fiber gratings can be tuned by etching fiber cladding [26–28]. Etching decreases propagation constants of the cladding modes, and the resonance wavelengths are shifted to long-wavelength side.

In this work, we focus on the structure formed by a section of double cladding fiber SM630 with depressed inner cladding. The transmission spectrum of this structure features two broad dips, which are formed by coupling between the core and cladding modes of the double cladding fiber. We have shown that the dips emerge at wavelengths where the propagation constants of two modes are almost equal [29]. This structure can successfully be used for sensing applications [30] due to good

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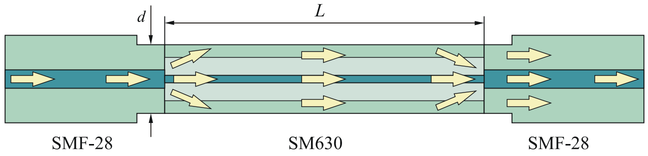

Fig. 1. Scheme of double cladding fiber structure with etched cladding.

sensitivity of the dips to bending, temperature, and external refractive index [31]. In this paper, we investigate experimentally the transmission spectra of the fiber-optic structure based on double cladding fiber, when the outer cladding is continuously etched. We analyze the behavior observed and compare it with simulation. We discuss the effect of cladding etching on sensitivity of the double-cladding structure to the external refractive index.

2. Double cladding fiber structure

The fiber structure that we investigate is formed by a section of double cladding SM630 fiber from 3M Specialty Optical Fiber spliced by using a conventional fusion splicer between two standard SMF-28 fibers from Corning. The double cladding fiber is cleaved to obtain a section of length $L = 10$ cm (Fig. 1). Light from a broadband source is launched into one end of the standard SMF-28 fiber. The other end of the standard fiber is connected to an optical spectrum analyzer. SM630 fiber is designed for single-mode operation at wavelength 630 nm; therefore, this fiber has a small core $r_{\text{co}} = 1.8$ μm ($\Delta = 0.325\%, \text{NA} = 0.12, \lambda_{\text{cutoff}} = 612$ nm). Also this fiber has an inner depressed cladding with radius $r_{\text{inn}} = 25$ μm. The outer cladding has radius $r_{\text{cl}} = 62.5$ μm and its refractive index is higher than that of the inner the cladding: $n_{\text{cl}} - n_{\text{inn}} = 0.0043$. The polymer jacket of the section of SM630 fiber was removed to avoid transmission of cladding modes to the jacket.

At the first splice between SMF-28 and SM630 fibers, the core mode of SMF-28 fiber is coupled to various modes of SM630 fiber due to unmatched refractive index profiles of the two fibers. These modes propagate through the section of SM630 fiber to the second splice, where they are coupled to the core mode of SMF-28 fiber, which is measured by the optical spectrum analyzer. The rest of light that is not coupled to the core mode goes into the cladding of SMF-28 fiber, where it is lost. Some part of light is scattered due to coupling to radiation modes and high-order modes having high losses at the fiber surface.

An earlier investigation of the structure has shown that its spectrum exhibits several dips [2]. The dips in the spectrum are formed at resonance wavelengths where two cladding modes have almost the same propagation constants. This happens because the external cladding of the double cladding fiber has refractive index higher than the refractive index of the inner cladding. At the resonance wavelength, these two modes have the same field profiles in the core region, and the core mode is coupled to both modes [29].

Transmission spectrum of the double cladding structure is shown in Fig. 2. Two main dips at wavelengths around 1185 and 1450 nm are observed. On the left side of the second dip, there is an additional narrow dip, which is probably related with the coupling to antisymmetric LP_{17} mode. The spectrum of this structure also exhibits irregular oscillations having amplitude increasing with wavelength. The oscillations are due to the interference of high-order cladding modes.

3. Etching of fiber cladding

The presence of dips in the spectrum of the double cladding fiber structure can be used for various sensing applications [30,31]. Therefore, it would be very useful to be able to control the wavelengths of the dips. These wavelengths are determined by the dispersions of cladding modes. As it was shown earlier, propagation constants of cladding modes can be changed by cladding etching [26–28]. We employ the same method and study how etching affects the spectrum and resonance wavelengths of the dips.

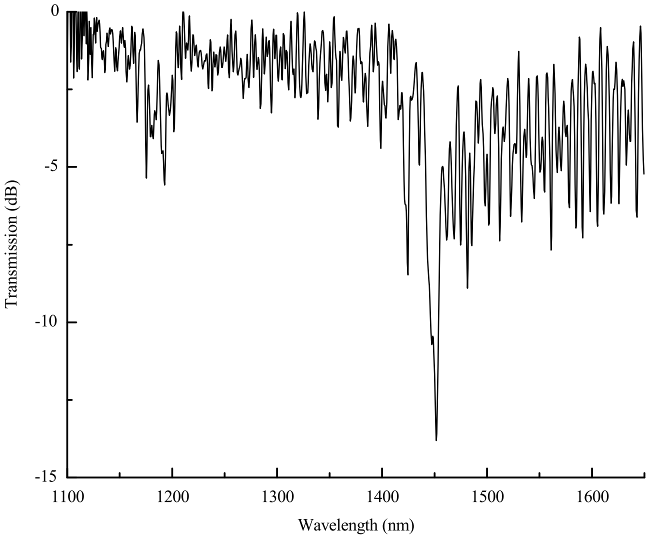

Fig. 2. Transmission spectrum of the double cladding fiber structure.

For etching the fiber, we used buffered oxide etch (BOE) that is a mixture of hydrofluoric acid and ammonium fluoride with 1:10 concentration. The section of uncoated double cladding fiber having a length of 10 cm was fixed straight between two holders with some tension. Then the fiber with the holders was immersed into the BOE, so that the fiber was retained straight. The radius of the fiber during etching was calculated based on etching time, initial radius of the fiber, and final radius measured after the etching was stopped. We assume that the etching speed was constant during the experiment.

An optical spectrum analyzer recorded transmission spectra during etching process every 60 s. As we have shown in Fig. 2, the initial spectrum of the structure exhibits two dips at around 1185 nm and 1450 nm. When the fiber is placed in the etchant, the dips start to shift to shorter wavelengths (Fig. 3). At the same time, their amplitudes decrease. When a dip comes to wavelength around 1100 nm, it vanishes.

New dips appear from longer wavelengths with decreasing cladding radius. Each new dip shifts faster and occupies broader range of the spectrum. The fifth new dip is the last, and it disappears, when the outer cladding is totally removed. Thus, by etching the fiber we can adjust position of the dip, its width, and we can choose fiber mode that is in resonance with the core mode.

4. Simulation of cladding modes

The dependencies of wavelengths of the spectral dips can be described theoretically. We use matrix method [24] to calculate the modes of fiber with four cylindrical layers: core, inner depressed cladding, outer cladding, and solution. The method is based on the conversion of Maxwell's equations into matrix form for matrices that describe transformation of a two-component field vector composed of tangential electric and magnetic fields between the layers. In general, electric field of a $LP_{\nu m}$ mode can be represented in the following form:

$$E_{\nu m} = AJ_\nu(ur) + BY_\nu(ur), \tag{1}$$

where $u = \sqrt{k_0^2\varepsilon - \beta^2}$ is the transverse component of the wavevector, $k_0 = \omega/c$ is the wavenumber, β is the propagation constant, and ε is the dielectric permittivity of layers. J_ν and Y_ν are the Bessel functions. u is real in the layer with the highest refractive indices—in the outer cladding, and the field amplitude is oscillating with radius r. The value