Chapter 1

Introduction

1.1 Review of Evanescent Wave Fiber Components and Fabrication Methods

Optical fiber components are essential for fiber-optic communication and sensing. They can be made by chemical-etching [1-3], fused-tapering [4-8], side-polishing [9-12], and laser ablation [13] techniques. To interact with the guiding wavelengths in fiber core, we can gain access to the evanescent field. Thus, a straightforward method is to remove a portion of the fiber cladding by chemical-etching, side-polishing or laser ablation until the evanescent field is accessed. Another way is to expand the mode field diameter by tapering the fiber using flame, filament [14], or laser. While the fiber core is tapered to a dimension of a few tens of micrometers, the mode field is expanded to the tapered fiber cladding which serves as a new guiding core. Among them, fused-tapering technique was widely adopted due to the easy, fast, and cost-effective fabrication processes. However, the guided mode is transferred into high-order modes through the tapered transition [15]. Moreover, the fused-tapered fiber coupler is somewhat polarization anisotropic so that a narrowband (< 10 nm) demultiplexer with a high channel isolation [16], particularly for applications like a high dropping efficiency add/drop multiplexer [17], and a fiber coupler with low polarization mode dispersion for 40 Gb/s fiber-optic systems are difficult to achieve. In contrast, the chemical-etching, side-polishing, and laser ablation techniques do not deform the fiber core and thus the polarization isotropy of the fiber devices can be better maintained. However, the chemical-etched fiber devices are too weak to use [2] whereas the laser-ablated fiber devices have the problems in that the ablation depth can not be accurately controlled. The side-polished fiber devices, on the contrary, are both mechanically strong and the polishing depth can be controlled within the accuracy of one micro-meters. Furthermore, the interaction length can be precisely determined by the curvature radius of the fiber. Unfortunately, for side-polishing, the processing time is too long and the cost is too high to make side-polished fiber devices widely used. However, side-polished fiber devices are still worthy of the investigation on new physical phenomena.

Once the evanescent field of the side-polished fiber can be accessed, variant kinds of mediums such as dispersive [18], gain [19,20], birefringent [21], nonlinear [22], absorption [23], electro-optical [24], metal [25,26] and so on are used as overlay for different kinds of functional communication or sensing devices. The above materials can also be used as a surrounding material for functional fused-tapered fiber devices. In brief, fused-tapered and side-polished fiber techniques are the most potential tools to meet the scientific research purposes, although only the fused-tapered fiber devices are popularly used nowadays.

1.2 Review of Dispersion of Evanescent Wave Fiber

Components

The dispersion of an evanescent wave fiber component is important to its spectral characteristics and the causes can be divided into two categories, material and waveguide dispersion. In general, the material dispersion came from the dispersion discrepancy between the fiber and the external medium while the waveguide dispersion resulted from the variations of the waveguide structure. For fiber devices, the relationship between the refractive index and wavelength changes with the variations of material and waveguide dispersion. Therefore, the spectral responses will vary accordingly and the influence is important when a wide range of wavelength is considered.

1.2.1 Material Dispersion

In evanescent wave fiber devices, since variant kind of material is combined with the fiber, the material dispersion may not be matched. When the material dispersion is un-matched, the spectral characteristics will be different from the original dispersion. The resulting spectral characteristics are similar to that of in a dispersive fiber [27-29] and a fundamental-mode cutoff phenomenon occurs. Normally, the index difference between the fiber core and cladding is almost wavelength independent. Therefore, all wavelengths longer than the second-mode cutoff wavelength can be well-confined to propagate in core with very low optical losses. However, in a dispersive fiber the refractive index dispersion curves of the core and fiber can cross at a point to induce fundamental-mode cutoff [18] since the material dispersion is un-matched between core and cladding [27]. Consequently, the wavelengths longer than the cutoff wavelengths suffer huge optical losses and the guiding is stopped. In general, the refractive index dispersion of the wavelength in proximity to the absorption bands of substances is highly dispersive. The Si–O bond in fused silica contributes to higher bandgap (~ 9 eV) [30] and phonon (~ 1100 cm^{-1}) energies than most of the covalently bonded optical polymers and which makes the fused silica have flatter and steeper dispersion slope than the polymers at visible and near-infrared wavelengths, respectively. Some polymers containing intermolecular hydrogen bonds [31] can turn out to have a higher phonon energy and steeper dispersion slope than fused silica at near-infrared wavelengths. At ultra-violet wavelengths, materials comprising the stronger ionic bonds (Li–F or Mg–F) or a polar covalent bond (Si–F), in terms of electronegativity difference, can make the absorption edge blue-shifted to exist a higher bandgap energy [32] and flatter dispersion slope than fused silica. Therefore, dispersive materials with different phonon energies can be applied on evanescent-wave fibers to make tunable fundamental-mode cutoff based on the discrepancy of material dispersion.

1.2.2 Waveguide Dispersion

In contrast to material dispersion, the waveguide dispersion due to the variations of waveguide structure is not so effective to the spectral characteristics. In side-polished fibers, the polishing depth and the curvature radius are the important parameters for waveguide dispersion. In fused-tapered fibers, the length, diameter, strain, bending, and dopant diffusion at the tapered region are the key issues for waveguide dispersion. In general, the variations of these parameters will mainly vary the dispersion slope of evanescent wave tunnelling, namely, the wavelength dependence. Usually, people discussed the influences of waveguide dispersion on fiber devices based on special fibers [33-36]. However, the waveguide structure can be locally changed to alter the waveguide dispersion for light propagation and the spectral responses of the fiber devices using standard fibers [37,38]. The electromagnetic field distribution is locally modified to vary the dispersion characteristics or to excite the higher-order modes [38]. Therefore, novel fiber devices can be achieved based on the variations of waveguide structure of the standard fiber in a small local area. In this dissertation, since the dispersion measurement instruments are not available, the influence of variations of waveguide structure on spectral characteristics is studied, instead of measuring the propagation constants, to show that the waveguide dispersion can be modified by waveguide structures.

1.3 Organization of the Dissertation

This dissertation consists of three related parts. In Chapter 2, the fabrication of side-polished fiber with a long-interaction length by using silicon V-grooves has been demonstrated. A side-polished fiber with its effective interaction length as long as around 20 mm was achieved and we can accordingly investigate the gain or nonlinear effects on side-polished fibers. Moreover, a long-interaction length is necessary for narrow-band fiber devices such as wavelength division multiplexer with narrow channel spacing or the add/drop multiplexers with fiber Bragg gratings in coupling region. In addition, we also make an arc fusion station by ourselves to fabricate fused-polished fiber couplers. The fused-polished fiber coupler, in contrast to fused-tapered fiber coupler, is less polarization sensitive which is advantageous for high-bit-rate fiber-optic communication systems due to the low polarization mode dispersion. The fused-polished fiber coupler may also be good for add/drop multiplexers since the dropping efficiency can be much better than that of the add/drop multiplexer using a fused-tapered fiber coupler. This is because there will be only symmetric and anti-symmetric modes to propagate in the coupling region and thus the best interference can be occurred at the dropping port for fused-polished fiber couplers.

In Chapter 3, the material dispersion discrepancy is introduced by using dispersive optical polymer clad onto side-polished fibers or fused-tapered fibers. Since the phonon vibration energy of the dispersive material is different from that of the silica fiber, the fundamental-mode cutoff can be achieved by applied low phonon energy optical polymer on the side-polished fiber or fused-tapered fiber. The cutoff efficiency is highly related to the cross angle between the refractive index dispersion curves between the dispersive material and silica fiber. A larger cross angle can lead to a sharper cutoff and a deeper rejection efficiency. The cutoff wavelength can be temperature tuned and can be incorporated into the Er^{3+}-doped fiber to make a high efficiency tunable fiber laser and amplifier. The tunable fiber amplifier can be tuned to cover the S- and C + L-bands by using the fundamental-mode cutoff filters discretely located in the standard silica-based single-cladding C-band Er^{3+}-dopes fiber. Based on this scheme, a S+C+L-band Er^{3+}-dopes fiber amplifier and a tunable fiber laser covering the S+C+L-band are feasible. On the other hand, the material dispersion discrepancy between gain medium and polished fiber can result in a poor pumping efficiency since the mode field diameter of the pump wavelength is smaller than that of the signal wavelength. Thus it is difficult to reach a high population inversion state for the gain medium and evanescent gain can only be obtain by pulse pumping. To solve this problem, a blazed grating is proposed to be used at the interaction region to diffract the pump light toward the gain medium. Therefore, the pump power can be more efficiently used and a cw-pumped evanescent gain is thus achieved.

In Chapter 4, the influence of the waveguide structure on spectral responses of side-polished photonic crystal fiber is investigated. Moreover, the fabrication method for side-polishing photonic crystal fiber is important since the air hole tubes will be broken during polishing, which causes significant optical losses for photonic crystal fiber. The ingoing slurry must be cleaned to avoid the huge losses. For side-polished photonic crystal fibers, the polishing depth and radius of the curvature are decisive to the waveguide loss, higher-order modes excitations, dispersion slope, and evanescent coupling. The side-polished photonic crystal fibers with different waveguide structures can be used to make novel fiber components. The concluding remarks and suggested future works are give in chapter 5.

References

[1] F. J. Liao and J. T. Boyd, “Single-mode fiber coupler,” Appl. Opt. **20**, 2731-2734 (1981).

[2] S. K. Sheem and T. G. Giallorenzi, “Single-mode fiber-optical power divider: encapsulated etching technique,” Opt. Lett. **4**, 29-31 (1979).

[3] C. D. Tran, K. P. Koo, and S. K. Sheem, “Single-mode fiber directional

coupler fabricated by twist-etching techniques," IEEE J. Quantum Electron. **17**, 988-991 (1981).

[4] B. S. Kawasaki, and K. O. Hill, "Low-loss access coupler for multimode optical fiber distribution networks," Appl. Opt. **16**, 1794-1795 (1977).

[5] B. S. Kawasaki, K. O. Hill, and R. G. Lamont, "Biconical-taper single-mode fiber coupler," Opt. Lett. **6**, 327-329 (1981).

[6] J. D. Love and W. M. Henry, "Quantifying loss minimization in single-mode fibre tapers," Electron. Lett. **22**, 912-913 (1986).

[7] R. P. Kenny, T. A. Birks, and K. P. Oakley, "Control of optical fibre taper shape," Electron. Lett. **27**, 1654-1656 (1991).

[8] G. Kakarantzas, T. E. Dimmick, T. A. Birks, R. Le Rouz, and P. St. J. Russell, "Miniature all-fiber devices based on CO_2 laser micro structuring of tapered fibers," Opt. Lett. **26**, 1137 (2001).

[9] R. A. Burgh, G. Kotler, and H. J. Shaw, "Single-mode fibre optic directional coupler," Electron. Lett. **16**, 260-261 (1980).

[10] S. P. Ma and S. M. Tseng, "High-performance side-polished fibers and applications as liquid crystal clad fiber polarizers," J. Lightwave Technol. **15**, 1554-1558 (1997).

[11] C. V. Cryan, and C. D. Hussey, "Fused polished single mode fibre couplers," Electron. Lett. **28**, 204-205 (1992).

[12] O. Laminger and R. Zengerle, "Determination of the variable core-to-surface spacing of single-mode fiber-coupler blocks," Opt. Lett. **28**, 211-213 (1987).

[13] R. J. Coyle Jr. et al., "Methods and apparatus for making optical fiber couplers," US patent no. 5,101,090 (1992).

[14] C. W. Wu, T. L. Wu, and H. C. Chang, "A novel fabrication method for

all-fiber, weakly fused, polarization beamsplitters," IEEE J. Photon. Technol. Lett. **7,** 786-788 (1995).

[15] T. A. Birks and Y. W. Li, "The shape of fiber tapers," IEEE J. Lightwave Technol. **10,** 432-438 (1992).

[16] M. N. McLandrich, R. J. Orazi, and H. R. Marlin, "Polarization independent narrow channel wavelength division multiplexing fiber couplers for 1.55 μm," IEEE J. Lightwave Technol. **9**, 442-447 (1991).

[17] E. Marin, R. Ghosh, J.-P. Meunier, X. Daxhelet, and S. Lacroix, "Bragg gratings in 2 × 2 symmetric fused fiber couplers: influence of the tilt on the wavelength response," IEEE Photonics Technol. Lett. **11**, 1434-1436 (1999).

[18] N. K. Chen, S. Chi, and S. M. Tseng, "Wideband tunable fiber short-pass filter based on side-polished fiber with dispersive polymer overlay," Opt. Lett. **29**, 2219-2221 (2004).

[19] N. K. Chen, S. Chi, L. Zhang, L. Hu, K. P. Chuang, Y. Lai, S. M. Tseng, and J. T. Shy, "CW-pumped evanescent amplification at 1.55 μm wavelength using highly Er^{3+}-doped glass over side-polished fiber," CLEO 2005 conference, Baltimore, USA, May 22-27, 2005. JWB61.

[20] W. V. Sorin, K. P. Jackson, and H. J. Shaw, "Evanescent amplification in a single-mode optical fibre," Electron. Lett. **19**, 820-821 (1983).

[21] S. G. Lee, J. P. Sokoloff, B. P. McGinnis, and H. Sasabe, "Fabrication of a side-polished fiber polarizer with a birefringent polymer overlay," Opt. Lett. **22**, 606-608 (1997).

[22] S. S. Johal, S. W. James, R. P. Tatam, and G. J. Ashwell, "Second-harmonic generation in Langmuir-Blodgett waveguide overlays on single-mode optical fiber," Opt. Lett. **24**, 1194-1196 (1999).

[23] W. V. Sorin, R. C. Youngquist, C. C. Cutler, and H. J. Shaw, "Single-mode-fiber saturable absorber," Opt. Lett. **9**, 315-317 (1984).

[24] E. S. Goldburt and P. St. J. Russell, "Electro-optical response of a liquid-crystalline fiber coupler," Appl. Phys. Lett. **48**, 10-12 (1986).

[25] M. N. Zervas and I. P. Giles, "Performance of surface-plasma-wave fiber-optic polarizers," Opt. Lett. **15**, 513-515 (1990).

[26] J. Homola, R. Slavik, and J. Ctyroky, "Interaction between fiber modes and surface plasmon waves: spectral properties," Opt. Lett. **22**, 1403-1405 (1997).

[27] J. W. Yu and K. Oh, "New in-line fiber band pass filters using high silica dispersive optical fibres," Opt. Commun. **204,** 111-118 (2002)

[28] K. Morishita, "Optical fiber devices using dispersive materials," J. Lightwave Technol. **7,** 198-201 (1989).

[29] K. Morishita, "Bandpass and band-rejection filters using dispersive fibers," J. Lightwave Technol. **7,** 816-819 (1989).

[30] P. N. Saeta and B. I. Greene, "Primary relaxation processes at the band edge of SiO_2," Phys. Rev. Lett. **70**, 3588-3591 (1993).

[31] M. Usui, M. Hikita, T. Watanabe, M. Amano, S. Sugawara, S. Hayashida, and S. Imamura, "Low-loss passive polymer optical waveguides with high environmental stability," J. Lightwave Technol. **14,** 2338-2343 (1996).

[32] H. Hosono, M. Mizuguchi, L. Skuja, and T. Ogawa, "Fluorine-doped SiO_2 glasses for F-2 excimer laser optics: fluorine content and color-center formation," Opt. Lett. **24,** 1549-1551 (1999).

[33] R. Zengerle and O. Leminger, "Narrow-band wavelength-selective directional couplers of dissimilar single-mode fibers," J. Lightwave Technol. **LT-5**, 1196-1198 (1987).

[34] C. J. Chung and A. Safaai-Jazi, “Narrow-band spectral filters made of W-index and step-index fibers,” J. Lightwave Technol. **10**, 42-45 (1992).

[35] M. Monerie, “Propagation in doubly clad single-mode fibers,” IEEE J. Quantum Electron. **QE-18**, 535-542 (1982).

[36] M. A. Arbore, “Application of fundamental-mode cutoff for novel amplifiers and lasers,” in *Optical Fiber Communication Conference OFC’05 (Optical Society of America, Wash*ington, D.C., 2005), paper OFB4.

[37] N. K. Chen, S. Chi, S. M. Tseng, and Y. Lai, “Wavelength-tunable fiber codirectional coupler filter based on asymmetric side-polished fiber coupler with local dispersive intermediate layer,” submitted to ECOC 2006 conference.

[38] N. K. Chen and S. Chi, “Influence of a holey cladding structure on the spectral characteristics of side-polished endlessly single-mode photonic crystal fibers,” accepted by Opt. Lett. (2006).