Chapter 5

Conclusions

5.1 Summary for the Dissertation

In this dissertation, the fabrication of side-polished fiber has been introduced and the influences of material dispersion and waveguide structure on spectral characteristics of evanescent wave fiber devices have also been investigated. The side-polishing and fused-tapering techniques were used to achieve variant kinds of fiber devices based on material dispersion discrepancy and variations of waveguide structures. In side-polishing, the side-polished fibers with a long effective interaction length using silicon substrates were employed to make fused-polished fiber couplers and narrow-band channel dropping filters. In material dispersion, the widely tunable fiber short-pass filters were demonstrated for the first time and were used in Er^{3+}-doped fiber to achieve broadband Er^{3+}-doped fiber amplifiers and high-tuning-efficiency fiber ring lasers. Moreover, a novel diffractive-pumping method was proposed for the first time to improve the pumping efficiency for evanescent amplification. In waveguide structure, the influence of the polishing depth and curvature radius on spectral characteristics of side-polished photonic crystal fiber were also proposed and experimentally observed for the first time. These investigations and demonstrations will be useful in communications, sensing, bio-photonics, and nano-photonics. The important results and contributions achieved in this dissertation are briefly summarized blew.

5.1.1 Evanescent wave fiber components

The side-polished fiber with a long effective interaction length can be mass produced using silicon V-grooves as the polishing substrates. The typical polishing time for a fiber with curvature radius of 800 cm is in 30 minutes. The alignment V-grooves could be simultaneously provided on polishing substrates to facilitate the alignment works for fiber couplers. The precision alignment could usually be down in a few minutes by using dummy fibers in alignment V-grooves. Moreover, the side-polished fibers could be further removed from the silicon substrates using chemicals and with a strong mechanical strength since the surface roughness is below a few tens of nano-meters inspected by atomic force microscopy. Without silicon substrates, the polished fibers can be fused to achieve fiber couplers in which the index-matching liquids at the interface between polished fibers are not necessary anymore. Thus, the fused-polished fiber coupler is environmentally stable and can serve in the high-bit-rate (> 40 Gb/s) fiber-optic communication systems due to its less sensitive to the state of polarization of light. In addition, the side-polished fiber coupler with a long effective interaction length is also good for high-adding/dropping-efficiency add/drop multiplexers since only symmetric and anti-symmetric modes are excited in the coupling region.

5.1.2 Influence of Material Dispersion

In material dispersion, widely tunable fiber short-pass filters with high cutoff efficiency have been demonstrated and analyzed. The cutoff efficiency is determined by the cross angle between the refractive index dispersion curves of the side-polished/fused-tapered fiber and the dispersive materials. The dispersive material with a larger thermo-optic coefficient can lead to a higher tuning efficiency of the cutoff wavelength. The tuning range can be wider than 400 nm (1250 ~ 1650 nm) while the tuning efficiency can be as high as 28.5 nm°C. This short-pass filter can be further incorporated into the Er^{3+}-doped fiber to achieve high tuning efficiency fiber ring laser. The tuning efficiency, tuning range, signal-ASE-ratio, and FWHM linewidth of the laser are 7.65 nm/°C, 26 nm (1569.8 ~ 1595.8 nm), 40 dB, and 0.5 nm, respectively. However, a short-pass filter is not sufficient to obtain the S-band optical gain in Er^{3+}-doped fiber. A broadband tunable Er^{3+}-doped fiber amplifier covering S- and the C+L bands have been demonstrated based on multistage short-pass filters in a 17-m-long standard single-cladding c-band Er^{3+}-doped fiber. The S-band gain can be as high as more than 18 dB with the 980 nm pump power of 135 mW.

On the other hand, although the material dispersion discrepancy can achieve short-pass filters since the phonon vibration energy of Si—O bond is much higher than most of the liquids and polymers, this phenomenon may induce the poor pumping efficiency of evanescent amplification. The gain mediums usually have a flatter dispersion slope than that of the silica fiber, the mode field diameter of the pump wavelength is thus smaller than that of the signal wavelengths, which make the population inversion state poor in the gain medium. In order to solve this problem, a blazed grating is employed in the interaction region to spatially separate the pump and signal wavelengths and the grating can diffract pump wavelength toward the gain medium to improve the population inversion. By doing so, a cw-pumped evanescent amplification with relative gain of 2 dB is achieved for the first time. The net gain will be obtained once the low-index highly Er^{3+}-doped glass is available.

5.1.3 Influence of Waveguide Structure

In waveguide structure, the influence of the polishing depth and curvature radius on dispersion characteristics have been investigated and observed for the first time in side-polished endlessly single-mode photonic crystal fibers. A side-polished photonic crystal fiber with a larger curvature radius or a deeper polishing depth can have a more dispersive characteristic. Moreover, the high-order modes can be excited from the short visible wavelength end under a deep polishing condition. In contrast to the conventional side-polished fiber, the evanescent field of the side-polished photonic crystal fiber is more tightly confined.

5.2 Suggestions for Future Work

Further works useful for fiber laser applications in communication systems, sensing, bio-photonics, and nano-photonics are described in below:

(a) In recent years, the S-band had become a new and important frequency band since it has a little bit higher dispersion than that in the C-band. Signals carried by the frequency with a little higher dispersion in fiber can more efficiently suppress the probability of four-wave-mixing. Thus, an Er^{3+}-doped fiber amplifier covering the S+C+L-bands using standard Er^{3+}-doped fiber is definitely a breakthrough for fiber-optic communications. In addition, a wideband master-oscillator power-amplifier is highly feasible based on the fundamental-mode cutoff.

(b) For laser applications, a widely tunable, single-frequency, high-power and low-noise fiber laser is very useful for material processing, medical treatments, spectrum analysis, and coherent or CATV communication systems. Based on the fundamental-mode cutoff phenomenon induced from material dispersion discrepancy between dispersive material and fiber, widely tunable, single frequency rare-earth-doped fiber lasers are promising for industrial, medical, and scientific applications.

(c) For ultra-low-noise evanescent amplification, a high efficiency all-fiber photon multiplier or photon counter could be successful in near future. This is a useful device in scientific research works.

(d) In sensing applications, the fundamental-mode cutoff can also be used to achieve all-fiber liquid refractometers, precision strain, bending, temperature, displacement sensors, and so forth.