

# Analysis of optical properties of fundamental-mode in waveguide tapered fibers

Cheng-Ling Lee\*, Kuo-Hsiang Lin, Nan-Kuang Chen

Department of Electro-Optical Engineering and Optoelectronics Research Center, National United University, No.1 Lien-Da, Kung-Ching Li, Miaoli 360, Taiwan, ROC

## ARTICLE INFO

### Article history:

Received 30 November 2009

Received in revised form 7 January 2010

Available online 20 February 2010

## ABSTRACT

An analysis of optical properties of fundamental-mode in waveguide tapered fibers is theoretically investigated and realized in this paper. The waveguide device is tapering an SMF-28 fiber to few tens of micrometers of diameter. For discussing the cladding size of waveguide structure affects the fundamental-mode cutoff (FMC) and the optical characteristics of the devices, to etch outer cladding to reduce the pure-silica cladding diameter proceeded and to compare optical properties of FMC with non-etched cladding tapered fibers. Numerical results show the cutoff wavelength of FMC is mainly dominated by the size of squeezed core and slope of FMC could be influenced by the size of pure-silica cladding.

© 2010 Elsevier Ltd. All rights reserved.

## 1. Introduction

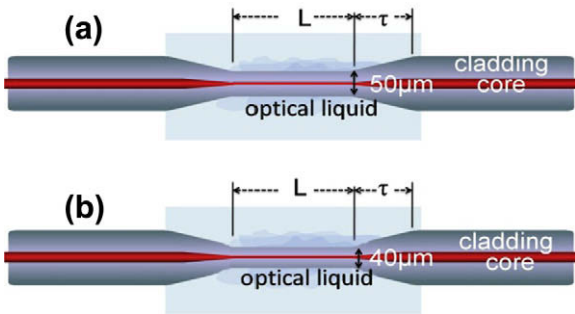
There are many research works and applications have been studied towards the optical characteristics of the tapered fibers because they have great applications in different technologies such as supercontinuum generation, pulse compression applications, useful optical fiber components and sensitive sensors [1–6]. A tapered waveguide must be regarded as a three-layer structure (core–cladding and external medium). The transmission spectra of optical characteristics are influenced by the refractive index of the external medium, refractive index profile of fiber and the tapered shape of the device. The dispersion characteristics of the tapered fiber can be easily modified by applying new optical materials such as optical liquids or optical polymers surrounding the tapered fiber. When the mode fields of the guiding lights penetrate the pure-silica cladding deep enough to overlap the outer new materials, the effective indices of guiding lights can be modulated and this is called the material dispersion engineering [5]. An optimal tapered fiber structure for a short-wavelength-pass filter with sharp and high cutoff efficiency has been achieved and demonstrated [7]. However, characteristics of SMF-28 tapered fiber of fundamental-mode cutoff (FMC) influenced by the waveguide structures (cladding diameters) have not discussed in the published papers so far. Therefore, in this paper, for the first time, an analysis of optical properties of fundamental-mode in waveguide tapered fibers is theoretically investigated and realized. The presented device is based on SMF-28 tapered fibers with few tens of micrometers of pure-silica cladding diameter which plays as a new core after tapering. To discuss the cladding size affects the fundamental-mode cutoff and the optical characteristics (transmission spectra) of the devices; the pure-silica cladding of the tapered fibers are

etched to reduce different sizes and immersed in the same optical liquid for comparing the waveguide properties.

## 2. Principle and tapered fiber structure

To investigate the influences of cladding size of the waveguide structure to the fundamental-mode in tapered fibers. Mode fields should be extended and covered over the whole waveguide structures. The simplest way to expose the mode fields of guiding lights is tapering technique and then modifies the structure of the waveguide tapered devices; therefore, propagation constant:  $\beta$  of the fundamental-mode will be changed. That means effective index ( $n_{eff} = \beta/k$ ,  $k$  is wave number:  $k = 2\pi/\lambda$ ), delay time:  $t$  (by differentiating  $\beta$  with  $k$ ) and chromatic dispersion (by differentiating  $t$  with  $\lambda$ ) of the device are varied, as well as fundamental-mode cutoff (FMC) and the optical characteristics of the tapered filters. The studied tapered fiber filters are made by tapering standard single-mode fibers (SMF-28) with the original ratio of diameters of core and cladding,  $D_{co}$  8.2  $\mu\text{m}$  and  $D_{cl}$  125  $\mu\text{m}$ , respectively. For simplification and practical considerations, three samples of tapered fibers with original cladding diameter  $D_{cl}$  of 50, 40, and 30  $\mu\text{m}$  which means that corresponding remained-core size  $D_{co}$  is about 3.28, 2.624, and 1.968  $\mu\text{m}$ , respectively. In our simulation study, we assume that germanium in the fiber core does not diffuses out into pure-silica cladding through the tapering processes. The tapered fibers are all chemically etched using hydrofluoric acid to remove part of silica cladding for reducing cladding diameter  $D_{cl}$  and to compare the curves of FMC wavelengths, FMC slopes and transmission losses with different waveguide structures of tapers. Fig. 1 shows diagram of the structure for the proposed devices: (a) before and (b) after etching with the original cladding diameter  $D_{cl}$  of 50  $\mu\text{m}$  and etched cladding diameter  $D_{cl}$  of 40  $\mu\text{m}$  with the identical core size.

\* Corresponding author. Tel.: +886 37 381732; fax: +886 37 351575.  
E-mail address: [cherry@nuu.edu.tw](mailto:cherry@nuu.edu.tw) (C.-L. Lee).



**Fig. 1.** Diagram of structure for the proposed devices: (a) original: 50  $\mu\text{m}$  and (b) etched: 40  $\mu\text{m}$  tapered fibers.

Here,  $L$  is uniform taper length, and  $\tau$  is taper transition length. The tapered fibers are all immersed in the same Cargille<sup>®</sup> optical liquids for implementing dispersion engineering through the control of the material dispersion. In this simulation case, the Cargille<sup>®</sup> liquid with the index of  $n_D = 1.456$  at 28.5 °C is fixed and used to be a surrounding medium.

In the numerical simulations, optical transmission spectra are calculated by the numerical finite difference beam propagation method (FD-BPM) to simulate the cut-off phenomena, propagation constant and propagation performance of electric or magnetic field of the wave through the devices [8,9].

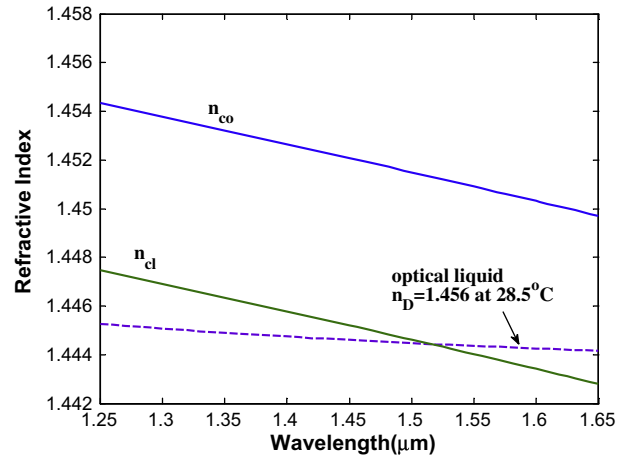
We consider the propagation of a circularly symmetric electric field  $\Psi(r, z) = \psi(r, z) \exp(-i\beta z)$  through an optical tapered fiber, the well known paraxial Helmholtz equation for the FD-BPM in cylindrical coordinates may be simplified as below [9]

$$2ikn_0 \frac{\partial \psi}{\partial z} = 2 \frac{\partial^2 \psi}{\partial r^2} + (k^2 n_0^2 - \beta^2) \psi \quad (1)$$

where  $\Psi$  is circularly symmetric electric field for the slowly varying field,  $\psi$  is amplitude of the  $\Psi$ ,  $k = 2\pi/\lambda$  is wave number,  $\beta(z)$  is the propagation constant at a point  $z$  in the tapered fiber, and  $n_0$  is a refractive index of the medium. By solving Eq. (1) using finite difference method [8,9] which adaptively recalculates the amplitude  $\psi$  of the waveguide structure at all  $z$  positions where the  $\beta$  varies in the direction of propagation axis with an initial condition input filed  $\psi_0(r, z=0)$ . Once the distribution  $\psi_L(r, z=L)$  and  $\beta(r=0, z=L)$  are calculated at the end of the tapered fiber at  $z=L$ , transmission can be obtained by normalizing the output power ( $\propto |\Psi_L|^2$ ) with the input power ( $\propto |\Psi_0|^2$ ) and the effective index ( $n_{\text{eff}}$ ) is calculated by  $n_{\text{eff}} = \beta/k$  at a certain wavelength  $\lambda$  at the same time. By scanning  $\lambda$ , transmission and effective index profiles versus  $\lambda$  can be readily obtained.

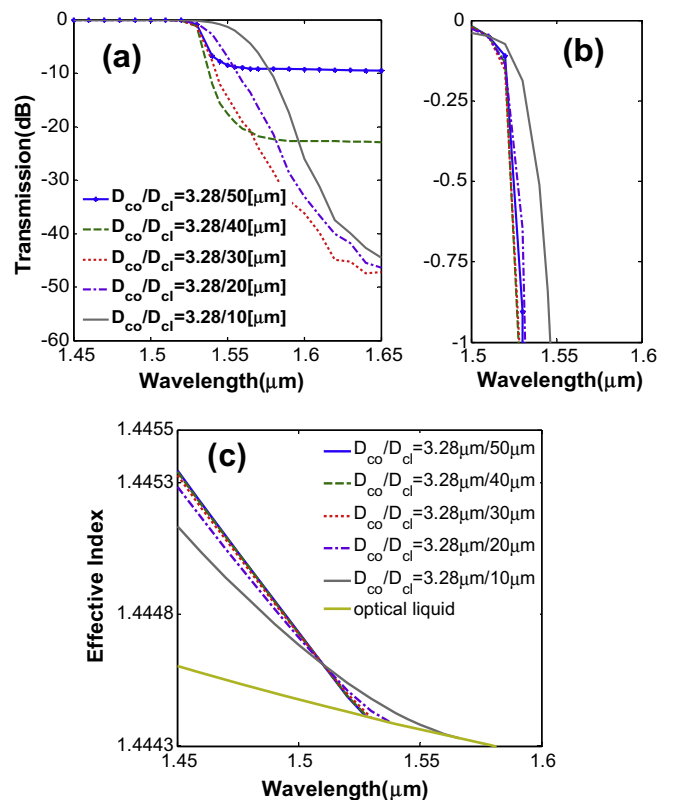
### 3. Simulation results and discussion

By applying FD-BPM approach, we have calculated the propagation characteristics of the presented devices to evaluate the influences by the cladding size of the waveguide taper. In our simulation, uniform tapered waist length of  $L = 1.5$  cm, and taper transition length  $\tau$  fixed 1.2 cm are used. The refractive index dispersion profiles of three-layer tapered structure are germanium doped core ( $n_{\text{co}}$ ),<sup>1</sup> pure-silica cladding ( $n_{\text{cl}}$ ), and optical liquid surrounding (Cargille<sup>®</sup>:  $n_D = 1.456$  at 28.5 °C for dashed line) respectively, shown in Fig. 2. Because chromatic dispersion is the sum of waveguide dispersion and material dispersion, therefore the effective index (as well as waveguide dispersion) can be controlled by the proper choice of the waveguide parameters (structures), while



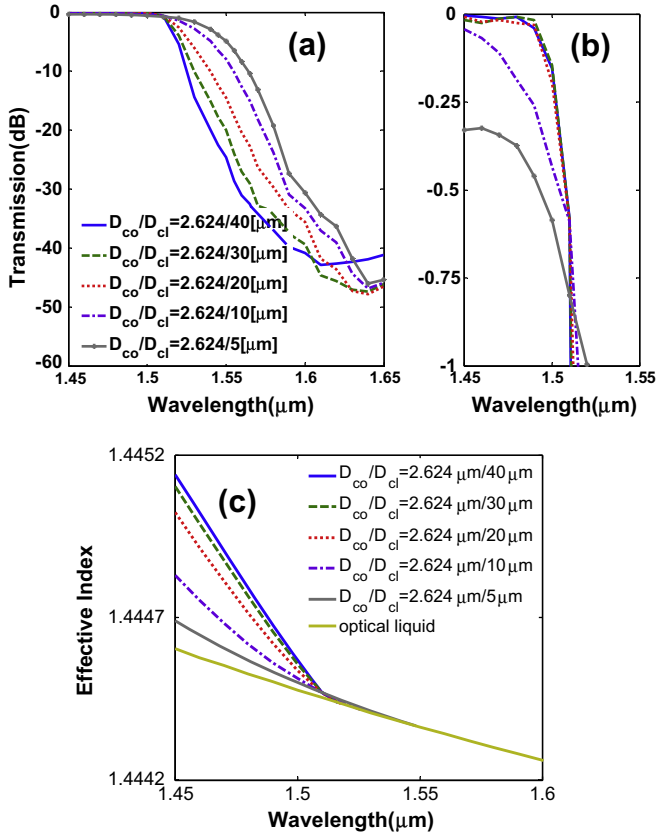
**Fig. 2.** Refractive index dispersion profiles for the SMF-28 tapered fiber and Cargille<sup>®</sup> optical liquid used in the simulation.

the material dispersion is almost independent of these parameters. Figs. 3–5 show different cladding sizes of waveguide tapered fibers where Figs. 3–5 show: (a) entire scale, (b) small scale of the transmission spectra to display cutoff wavelengths and loss more clearly, and (c) calculated effective indices for different structures of devices. From the simulation results, one can see the slopes of fundamental-mode cutoff (FMC) and cutoff wavelengths in the transmission spectra can be influenced and changed when the waveguide structures of the tapered fiber change. The cutoff condition when normalized propagation constant  $b$  for fundamental-mode approaches to zero, which  $b$  is defined by [10]:

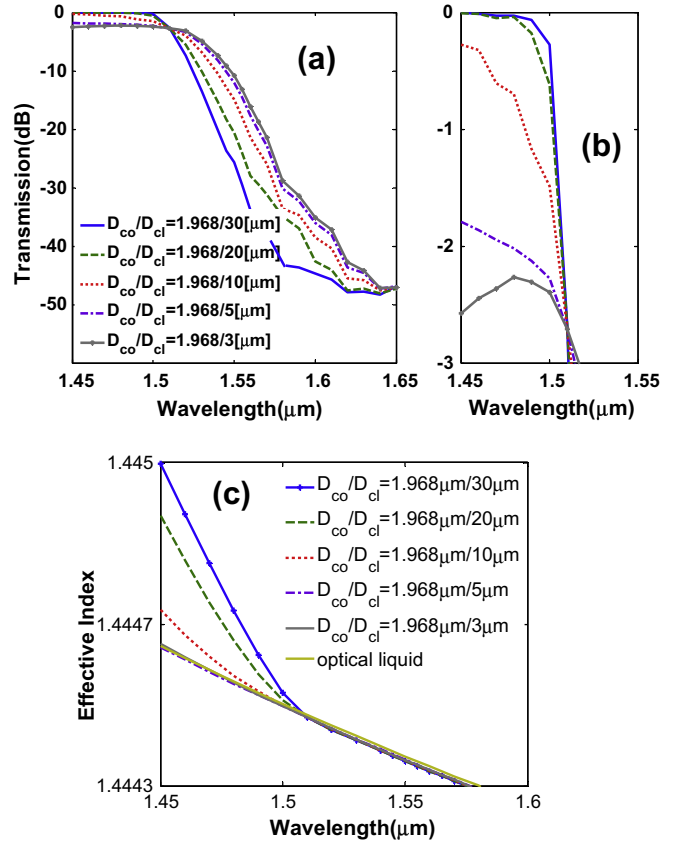


**Fig. 3.** (a and b) Transmission spectra of etched tapered fibers with initial  $D_{\text{cl}}$  of 50  $\mu\text{m}$  and etched of 40, 30, 20 and 10  $\mu\text{m}$  for the same remained-core size  $D_{\text{co}}$  of 3.28  $\mu\text{m}$  and (c) corresponding effective indices.

<sup>1</sup> For interpretation of color in Figs. 1–6, the reader is referred to the web version of this article.



**Fig. 4.** (a and b) Transmission spectra of etched tapered fiber with initial  $D_{cl}$  of 40  $\mu\text{m}$  and etched of 30, 20, 10 and 5  $\mu\text{m}$  for the same remained-core size  $D_{co}$  of 2.624  $\mu\text{m}$  and (c) corresponding effective indices.



**Fig. 5.** (a and b) Transmission spectra of etched tapered fiber with initial  $D_{cl}$  of 30  $\mu\text{m}$  and etched of 20, 10, 5 and 3  $\mu\text{m}$  for the same remained-core size  $D_{co}$  of 1.968  $\mu\text{m}$  and (c) corresponding effective indices.

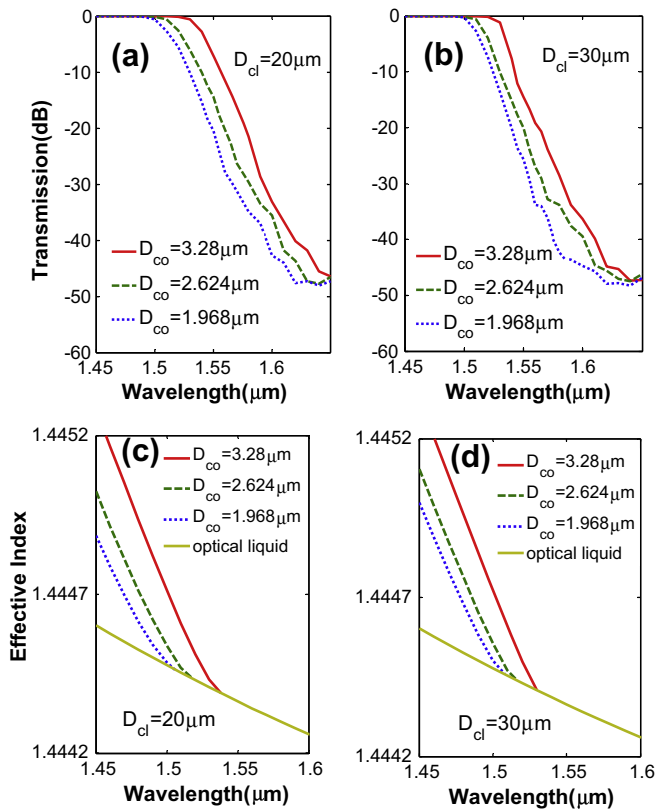
$$b = \frac{n_{eff}^2 - n_D^2}{n_c^2 - n_D^2} \quad (2)$$

where  $n_{eff}$  is effective index of fundamental-mode of the device,  $n_c$  and  $n_D$  are refractive indices of the new core and surrounding for the tapered fiber, respectively.

In the Eq. (2),  $b$  should be limited within  $0 < b < 1$  for the guided mode and the cutoff condition is expressed as  $b \rightarrow 0$ . In Fig. 3, the cutoff wavelengths of the devices are not affected strongly because mode field would be confined very well in the transmission wavelength region when the cladding diameter  $D_{cl}$  is 50, 40 and 30  $\mu\text{m}$  because remained core of 3.28  $\mu\text{m}$  is still large and dominants the behavior of the fundamental guided mode.

In Fig. 3a, transmission wavelength region (around 1.45–1.55  $\mu\text{m}$ ), fundamental-mode would not loss and transmission is almost equal one. It can be clearly seen, when  $D_{cl}$  is 50  $\mu\text{m}$ , the fundamental-mode field would not stretch out more and not be affected by external medium which will not resulted much loss in wavelengths of stopband (around 1.55–1.65  $\mu\text{m}$ ). However, the sharpest slopes of FMC is found when  $D_{cl} = 40 \mu\text{m}$  because in this case the effective index of the fundamental-mode changes suddenly in the cutoff wavelength by which a high rejection efficiency can be readily obtained. One can see Fig. 3b for more clearly and can find the cutoff wavelengths are almost the same when cladding sizes are 50, 40 and 30  $\mu\text{m}$  while cutoff wavelength of 10  $\mu\text{m}$  cladding is longer than those of 20  $\mu\text{m}$  cladding. The results can be explained by the calculated effective index of the tapered fibers with the same remained core while silica cladding sizes are different which is shown in Fig. 3c. In Fig. 3c, cross points (cutoff wavelengths) of  $n_{eff}$  and  $n_D$  (external medium) profiles tend very slightly toward longer wavelength when cladding sizes reduced

by etching, especially under  $D_{cl} < 30 \mu\text{m}$ . The  $n_{eff}$  profile tends to lower and flatter when  $D_{cl}$  reduces. It is because that the tapered cladding plays the role of the new core and the fundamental-mode field spreads out into non-dispersive external medium more when the diameter of tapered cladding decreases. When original cladding size of tapered fiber are  $D_{cl} = 40$  and 50  $\mu\text{m}$ , the fundamental-mode field is confined in the new core very well and the properties of transmission spectra of the both cases are similar which are different with those cladding sizes are etched – 30, 20 and 10  $\mu\text{m}$ . It also can be demonstrated by the mode field distribution from the published paper [7], if the diameter of tapered fiber  $< 33 \mu\text{m}$  (the cladding size), the fundamental-mode field will be strongly extended into surrounding region and subjected a smoother cutoff slope of the transmission spectra due to the effective index of fundamental-mode is getting flat since optical liquid is non-dispersive than silica which are shown in Fig. 2. But in the cases of cladding sizes 50 and 40  $\mu\text{m}$  which are shown in blue-solid and green-dashed lines in Fig. 3c, respectively; mode are confined well in short wavelengths with higher effective index while sharply changed in the cutoff condition and suffers large loss at rejection band. Therefore, high rejection efficiency at the cutoff wavelengths can be obtained on these two cases. It is worth to know, effective index slopes (cross angle between effective index and surrounding) will strongly affect the slopes of FMC. From the above results, a high effective index slope (large cross angle) will make a sharp slope of FMC because it is caused by a rapid variation of effective index within narrow wavelength range. Again, Fig. 4 shows the original tapered size of the cladding is 40  $\mu\text{m}$  with remained-core size is reduced to be 2.624  $\mu\text{m}$ . From Fig. 4a and b, one can see the optical properties of FMC are very similar with



**Fig. 6.** Transmission spectra of the same tapered cladding diameters: (a) 20  $\mu\text{m}$  and (b) 30  $\mu\text{m}$  with different remained core diameters; and (c and d) corresponding effective indices.

those of Fig. 3. However, in this case; thinner cladding leads to higher loss when compared with the case of original  $D_{cl}$  of 50  $\mu\text{m}$ , especially when cladding size is etched to 5  $\mu\text{m}$ . It is because fundamental-mode field stretches out into non-dispersive external medium more and that will cause the cutoff slopes more flattening. From Fig. 4c, the slopes of the effective indices of this case are more flattening than those of the case in Fig. 3c. Therefore, slopes of rejection profiles are more flattening and the cutoff wavelengths shift toward longer wavelengths when cladding sizes reduces. Especially, when  $D_{co}/D_{cl} = 2.624/5 \mu\text{m}$ , cutoff wavelength tends to longer wavelength (shown on gray-solid line of Fig. 4c) and in this case, the mode field is strongly loss due to such a small new core (shown on gray-solid line of Fig. 4b). It also can be observed in Fig. 5 with the case of original tapered  $D_{cl} = 30 \mu\text{m}$ . It is about 1 dB loss around cutoff wavelength when the cladding size is etched and reduced to 10  $\mu\text{m}$  and much higher loss (>3 dB) can be observed when cladding size is less than 5  $\mu\text{m}$  since most of fundamental-mode power is dissipated in the external liquid (new cladding). Therefore, the effective index of the structures  $D_{cl} < 5 \mu\text{m}$  are near optical liquid, shown in Fig. 5c. In order to analyze and compare the waveguide dispersion affects on the cutoff characteristics of the transmission spectra, a comparison analysis for the same cladding size with different remained core diameters is shown in Fig. 6. Fig. 6a and b displays the transmission spectra for the same cladding size with  $D_{cl}$  of 20  $\mu\text{m}$  and 30  $\mu\text{m}$ , respectively and Fig. 6c and d shows the corresponding effective indices dispersion profiles. From the results of Fig. 6c and d, the cutoff wavelength shifts toward short wavelength when remained core

diameters ( $D_{co}$ ) decreases while the slopes of cutoff efficiencies (slopes) are almost the same since they are with the same cladding sizes ( $D_{cl}$ ).

From the above simulated results, the cutoff wavelength is mainly dominated by the remained-core sizes and the slopes of fundamental-mode cutoff (FMC) will be influenced by the cladding sizes. On the other words, the slopes of FMC are strongly dependent on the ratio of fundamental-mode field stretched out to the non-dispersive optical liquid surrounding. Such a tapered filter can be very useful as a short pass filter, shaped filter for sensing application, laser technology and fiber communication systems. In other words, by choosing a proper core and cladding size with a selected external medium, an optimal and practical filtering device with desired cutoff characteristics of transmission can be obtained through the waveguide dispersion controlled processes.

#### 4. Conclusion

In this paper, we have investigated and demonstrated that remained core and cladding sizes are important factors for the cutoff wavelengths, slopes of cutoff, and transmission loss in the SMF-28 tapered fibers. From the analytical simulation results, concentration and size of remained core are mainly dominating the cutoff wavelength of spectra of the fundamental-mode cutoff (FMC). On the other hand, diameter of cladding and refractive index of surrounding will control the amount of fundamental-mode field extended to the surrounding region and the slope of FMC will be strongly influenced as well. Therefore, the cutoff efficiency, cutoff wavelengths and transmission characteristics could be optimized and synthesized through the waveguide dispersion control processes by choosing a proper core and cladding size with a selected external medium.

#### Acknowledgments

This research is supported by the National Science Council of the Republic of China, NSC 97-2221-E-239-012 and NSC 98-2221-E-239-002-MY2.

#### References

- [1] Veilleux C, Lapierre J, Bures J. Liquid-crystal-clad tapered fibers. *Opt Lett* 1986;11:733–5.
- [2] Corres JM, Arregui FJ, Matias IR. Sensitivity optimization of tapered optical fiber humidity sensors by means of tuning the thickness of nanostructured sensitive coatings. *Sensors Actuat B* 2007;122:442–9.
- [3] Diez A, Andres MV, Cruz JL. In-line fiber-optic sensors based on the excitation of surface plasma modes in metal-coated tapered fibers. *Sensors Actuat B* 2001;73:95–9.
- [4] Birks TA, Wadsworth WJ, Russell PStJ. Supercontinuum generation in tapered fibers. *Opt Lett* 2000;25:1415–7.
- [5] Chen NK, Hsu KC, Liaw SK, Lai Y, Chi S. Influence of depressed-index outer ring on evanescent tunneling loss in tapered double-cladding fibers. *Opt Lett* 2008;33:1666–8.
- [6] Hu J, Marks BS, Menyuk CR. Pulse compression using a tapered microstructure optical fiber. *Opt Exp* 2006;14:4026–36.
- [7] Chou S-Y, Hsu K-C, Chen N-K, Liaw S-K, Chih Y-S, Lai Y, et al. Analysis of thermo-optic tunable dispersion-engineered short-wavelength-pass tapered-fiber filters. *IEEE J Lightwave Technol* 2009;27:2208–15.
- [8] Scarmozzino R, Osgood Jr RM. Comparison of finite-difference and Fourier-transform solutions of the parabolic wave equation with emphasis on integrated-optics applications. *J Opt Soc Am A* 1991;8:724–31.
- [9] Moar PN, Huntington ST, Katsifolis J, Cahill LW, Roberts A, Nugent KA. Fabrication, modeling, and direct evanescent field measurement of tapered optical fiber sensors. *J Appl Phys* 1999;85:3395–8.
- [10] Okamoto K. *Fundamentals of optical waveguides*. Academic Press; 2006 [chapter 3].