Influence of depressed-index outer ring on evanescent tunneling loss in tapered double-cladding fibers

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A tapered fiber with a depressed-index outer ring is fabricated and dispersion engineered to generate a widely tunable (1250–1650 nm) fundamental-mode leakage loss with a high cutoff slope (−1.2 dB/nm) and a high attenuation for stop band (>50 dB) by modification of both waveguide and material dispersions. The higher cutoff slope is achieved with a larger cross angle between the two refractive index dispersion curves of the tapered fiber and surrounding optical liquids through the use of depressed-index outer ring structures in double-cladding fibers. © 2008 Optical Society of America

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Dispersion characteristics of optical fibers have played important roles in fiber-photonics. For single-mode fibers, the chromatic dispersion is composed of the material and waveguide dispersions, and the techniques of modifying the propagation constant $\beta(\omega)$ by using different materials or structures [1–10] can be called the dispersion engineering. Since the variations of $\beta(\omega)$ can also substantially affect the propagation losses of lights through the mode cutoff effects, the dispersion engineering on $\beta(\omega)$ has been employed to achieve fundamental-mode cutoff ($LP_{01\text{-}C}$) filters [5–10]. Actually, the waveguiding properties of optical fibers are mainly determined by the core diameter and the refractive index dispersion (RID) $n(\lambda)$ of core and cladding, which can reveal the spectral dependence of the mode field diameter (MFD). The two extreme cases of wavelength (λ)-independent and highly λ-dependent MFD, respectively, are in accordance with the endlessly single-mode fiber [11] and the $LP_{01\text{-}C}$ fiber filters [12]. The $LP_{01\text{-}C}$ fiber filters with a high cutoff slope are essential for silica-based *S*-band erbium-doped fiber amplifiers and lasers [5,7,12]. The cutoff slope can be increased by modifying waveguide dispersion [6–8] or by modifying the material dispersion [5,9,10]. A sharp $LP_{01\text{-}C}$ filter providing highly λ-dependent losses [12] is definitely useful for wavelength tuning in ultrahigh gain efficiency fiber lasers, but the achieved cutoff slopes by simply modifying either one of the dispersions are not good enough to clearly separate the guiding and antiguiding wavelengths.

In this Letter, we propose a new structure of tapered fibers with a depressed-index outer ring surrounded by optical liquids to achieve the sharpest $LP_{01\text{-}C}$ than ever reported (to our knowledge). The depressed-index outer ring is made by directly tapering the double-cladding fiber (DCLF) until the thickness of depressed-index outer cladding approaches a few micrometers. Unlike the refracting leaky loss [13] using dispersive fibers [9] or tapered SMF-28 fibers [12], the dispersion-induced propagation loss in a tapered DCLF comes from the tunneling leaky loss [13], which makes the MFD more λ-dependent when lights tunnel through the thinned depressed-index outer ring. In terms of waveguide dispersion, the MFD inside the thinned depressed-index silica ring distributed over the pure silica becomes highly λ-dependent when the original core is tapered to have a wavelength scale. This explains why the tapered SMF-28 has the best cutoff when the tapered diameter is around 30 μm [12]. Furthermore, the depressed-index outer ring in tapered DCLFs, usually F-doped with the thickness in the wavelength scale, can confine the shorter wavelengths more tightly than the longer wavelengths to produce a higher cutoff slope, similar to that in a depressed-index inner cladding fiber [7,8]. In terms of material dispersion, the optical materials with different dispersion characteristics than silica had been used to surround the tapered fiber for frustrating the total internal reflection to achieve $LP_{01\text{-}C}$ [5,9,10]. Inspired by the above arguments, in this Letter a DCLF with a low-index F-doped silica outer cladding is tapered down to have a uniform waist diameter D of 22 μm. The thinned F-doped ring with a thickness of 3.1 μm serves as the depressed-index outer cladding for the tapered DCLF when commercial Cargille index liquids are used to surround the tapered section. For the $LP_{01\text{-}C}$ filter so made, the cutoff slope is at least higher than −1.2 dB/nm over 1250–1650 nm, steeper than that in previous works [5–10]. Here the cutoff slope is defined as the slope of a line passing through the two points at 10 and 40 dB loss in a roll-off curve.

In more detail, the tunable $LP_{01\text{-}C}$ filter with a high cutoff slope and high stop-band rejection efficiency is

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achieved based on a tapered DCLF (Fibercore: SMM900) undoped with gain atoms and immersed in Cargille liquids. The DCLF consists of a Ge-doped silica core, an inner pure silica cladding of 90 μm diameter, and an outer F-doped depressed-index cladding of 125 μm diameter, as shown in Fig. 1(a). The tapered DCLFs at different diameters are also shown in Figs. 1(b) and 1(c). The details of fabrication and principle for the DCLF LP$_{01\text{-C}}$ filters are the same as those for fused-tapered LP$_{01\text{-C}}$ filters using SMF-28 [5,12]. Figure 1 shows the cross-sectional structures of the tapered DCLFs with D equal to 125, 70, and 22 μm, respectively, examined under a 1000× CCD microscope. Through the tapering processes, the F-doped outer cladding starts to affect waveguide dispersion when it is thinned down to be with the thickness in the wavelength scale. In contrast to standard tapered SMF-28, the thinned F-doped silica ring in the tapered DCLF provides a better field confinement, and thus a smaller D is necessary for accessing the evanescent field. A Cargille liquid is applied to surround the tapered DCLF as a new cladding material for generating tunable LP$_{01\text{-C}}$. The simulation works presented below on the spectral responses of the devices can help to clarify the influence of the material and waveguide dispersion on the cutoff slope. Since the Sellmeier coefficients of F-doped silica are not available, we consider approximately 1 mol. % F-doped silica as the outer ring of SMM900, and the material dispersion characteristics of its RID curve together with those of fused silica and Cargille liquids at 25°C are shown in Fig. 2. The effective fundamental mode index n_{eff} of tapered SMF-28 and SMM900 surrounded by Cargille liquids at different D are shown in Fig. 2 as well. From Fig. 2, the F-doped silica has a flatter RID slope $|\mathrm{d}n/\mathrm{d}\lambda|$ than silica to confine the shorter wavelengths better than the longer wavelengths, and thus the $|\mathrm{d}n/\mathrm{d}\lambda|$ of the n_{eff} of the tapered SMM900 is steeper than that of tapered SMF-28. The n_{eff} of tapered SMM900 and SMF-28 are calculated by considering the tapered fibers immersed in the Cargille liquids A ($n_D=1.454$) and B ($n_D=1.456$), respectively. The thickness d of the thinned F-doped silica ring in tapered SMM900 is 3.1 and 1.96 μm for $D=22$ μm and $D=14$ μm, respectively. When D is larger than 30 μm, d is still too large, making the evanescent field inaccessible, and thus no cutoff can be observed over 1250–1650 nm even when a high index ($n_D>1.6$) liquid is applied.

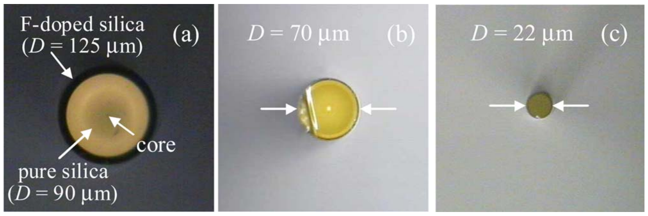

Fig. 1. (Color online) Cross-sectional views of the SMM900 at different tapered diameters.

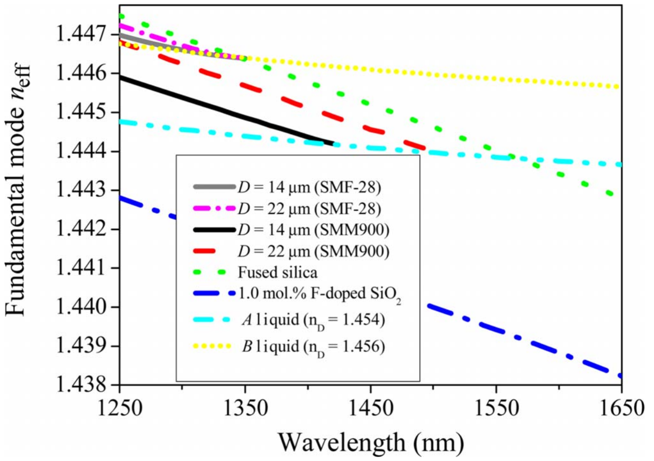

Fig. 2. (Color online) Estimated RID of the fused silica, 1 mol. % F-doped silica, and Cargille liquids as well as the effective index of tapered SMF-28 in B liquid and tapered SMM900 in A liquid at different D.

The simulated spectral responses using the beam propagating method (BPM) for the tapered SMF-28 and SMM900, immersed in A liquid, with $D=14$ and 22 μm are shown in Fig. 3(a). The waveguide dispersion dominates more over the cutoff wavelength in DCLF structures since the variation of D produces a wavelength shift of LP$_{01\text{-C}}$, but the high cutoff slope is

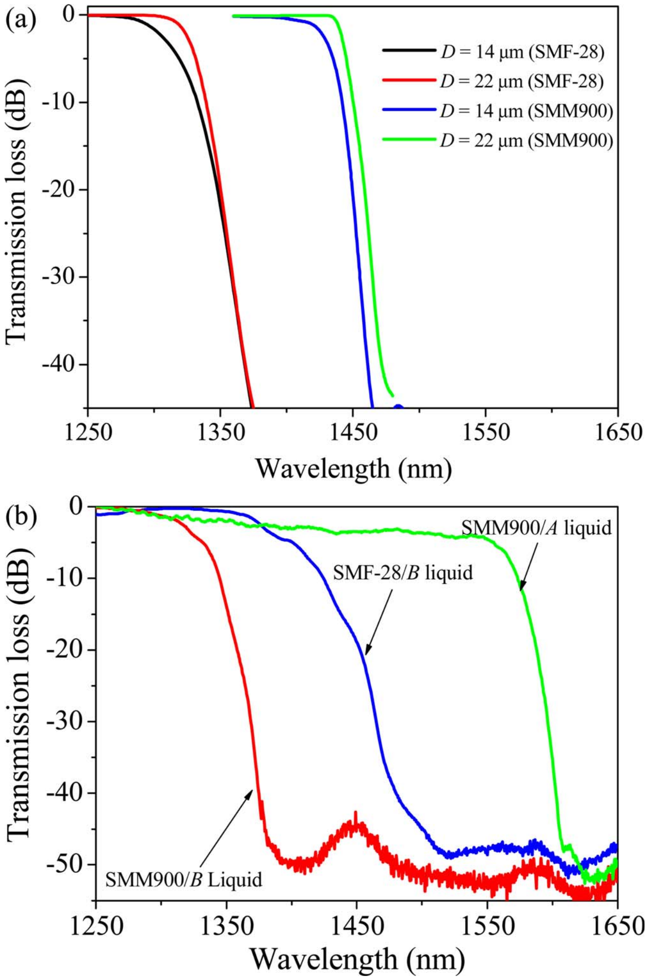

Fig. 3. (Color online) (a) Simulated spectral responses of tapered SMF-28 and SMM900 using A liquid and (b) measured spectral responses of tapered SMF-28 and tapered SMM900 using A and B liquids with $D=14$ μm.

still unchanged. In measurement, a broadband (1250–1650 nm) white light from multiple superluminescent diodes is launched into the tapered DCLF, and the Cargille liquid is used to cover the whole tapered section. In Fig. 3(b), the transmission spectra of the tapered SMM900 filter respectively immersed in A and B liquids are compared with that of the tapered SMF-28 filter (with a uniform waist length D_L around 10 mm) immersed in the B liquid when both have the same D of 14 μm at 25°C. The cutoff slope for the tapered SMM900 is −0.88 dB/nm, which obviously provides a steeper slope than that of the tapered SMF-28 (−0.49 dB/nm). This again shows that the MFD is more λ-dependent for tunneling leaky modes than in the refracting leaky modes. The thinned F-doped silica ring makes the n_{eff} of tapered SMM900 lower than that of fused silica, and it turns out to produce a shorter cutoff wavelength than tapered SMF-28 when both fibers are immersed in the B liquid. Figure 4(a) shows the transmission spectra of the tapered SMM900 at different D with the D_L around 5 mm and the total elongation length about 45 mm. When D gradually goes down to 10 μm, the cutoff slopes are getting flatter since the waveguide itself begins to lose the strong field confinement ability. However, when D is larger than 30 μm, the F-doped silica ring can strongly confine the lights inside the fiber, and the evanescent field is not accessible. The experimental results indicate that the $\text{LP}_{01\text{-C}}$ with a high cutoff slope can be achieved when D is around 20 μm. Figure 4(b) depicts the transmission spectra of tapered SMM900 (D_L and total elongation length is about 10 and 40 mm), respectively, with a current highest cutoff slope of −1.2 dB/nm at $D=22$ μm at different temperatures using an IR lamp, which inconsequentially leads to unrecorded temperatures.

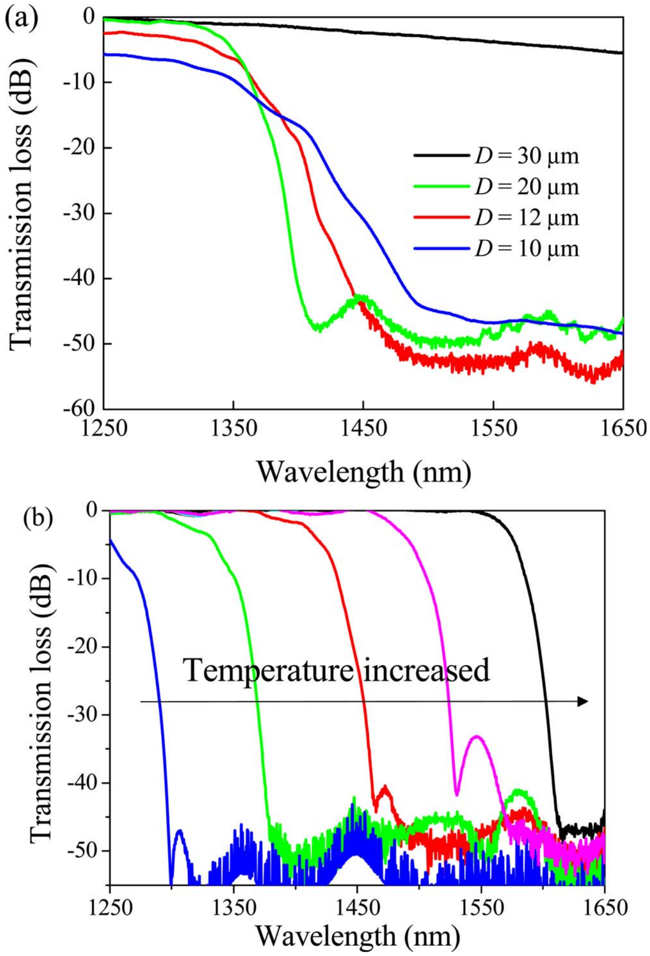

Fig. 4. (Color online) Spectral responses of tapered SMM900 with (a) different D using B liquid at room temperature and (b) $D=22$ μm at different heating temperatures using an IR lamp.

In conclusion, we have demonstrated a new structure of widely tunable $\text{LP}_{01\text{-C}}$ tapered fiber filters with a high cutoff slope over 1250–1650 nm based on the depressed-index outer ring over a tapered fiber. The cutoff slope can be higher than −1.2 dB/nm, whereas the rejection efficiency can be above 50 dB. The cutoff slope is much steeper than that of conventional depressed inner cladding fibers as well as tapered SMF-28 fibers. The achieved high cutoff efficiency should be advantageous for more efficient wavelength tuning in ultrahigh gain efficiency fiber lasers.

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