Observation of tunable bandpass characteristics in a hollow-optical-fiber–microstructured-fiber composite structure using bend-loss edge-shift effects

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Two optical fibers with different types of air-hole imbedded structures were serially concatenated to provide novel transmission characteristics. Bending sensitive shifts of the fundamental mode cutoff in a hollow optical fiber and a hexagonal microstructured holey fiber were found to be in opposite directions, which defines a new window with flexible tuning of the center wavelength and the bandwidth of transmission by independent bending radii control of the fibers. The concatenated composite structure provided useful optical transmission window management ranging from 400 to 1700 nm along with a tunable pass bandwidth of 300–1000 nm and a sideband rejection efficiency better than 20 dB. © 2008 Optical Society of America

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Owing to their novel structures and unique guiding properties, microstructured fibers (MSFs) with periodic air holes have been the focus of recent optical fiber research. Tremendous efforts have been exerted to utilize and clarify characteristics of guided modes in MSFs, such as endlessly single-mode guidance, high birefringence, and anomalous dispersion [1,2], to name a few. One of the notable features of MSFs, which has not been fully exploited yet in device applications, is the existence of the short-wavelength bend-loss edges (SW-BLEs) [3–5]. This peculiar SW-BLE limits the operation bandwidth, but it enables us to use it as a kind of long-wavelength pass filter. As an alternative air-hole imbedded fiber structure to MSFs, a hollow optical fiber (HOF) has been developed to provide versatile device applications in optical communications and sensing [6]. The HOF has a unique three-layered structure composed of a central air hole, a germanosilicate glass ring-core, and a silica cladding, which extends the optical field distribution further into the cladding region. This unique waveguide structure of the HOF has provided the fundamental mode cutoff at a long wavelength [6,7], and the HOF shows a bend-sensitive long-wavelength bend-loss edge (LW-BLE) providing short-wavelength pass characteristics, which is a clear contrast to the MSF’s long-wavelength pass nature.

In this Letter, we experimentally examine the transmission characteristics of serially concatenated HOFs and MSFs to take advantage of contrasting BLE shifts of two air-hole imbedded fibers under macrobending [8]. Novel bandpass transmission characteristics were successfully realized to flexibly tune the center wavelength and bandwidth. Compared with a recent composite structure based on a solid core photonic bandgap fiber and a Bragg fiber [9], the proposed structure could provide a wider tunable range, high stability, and lower insertion loss.

A schematic of the proposed device is shown in Fig. 1. The composite fiber structure consists of an MSF and an HOF, which are spliced together using conventional single-mode fiber (SMF) segments in between. The MSF and the HOF are then put under the macrobending with the radii of curvature, $R_1$ and $R_2$. Redshift of SW-BLE in the MSF and blueshift in LW-BLE in the HOF are then combined to generate unique bandpass characteristics that could be tuned by independent control of bending radii. The MSF, whose cross section is shown in Fig. 1 (top left), was fabricated by using stack-and-drawing of capillaries and silica rods along with a pressure control process. The MSF had three layers of hexagonally structured...
air holes whose diameters decreased from 2.9 to 1.5 µm in the radial outward direction. The air-hole pitch and the outer diameter of the MSF were about 8.8 and 110 µm, respectively. The MSF was spliced to a standard SMF, Corning SMF-28, to lead-in/out ports. The bend-loss properties of the MSF were experimentally characterized by measuring the transmission spectra for various bend radii, \( R_1 \), with a single-turn bend as in Fig. 2(a). The solid curve indicates the transmission spectrum of the straight MSF without bending. The noticeable amount of attenuation near 1200 nm was originated from the higher-order mode cutoff of the spliced lead-out SMF.

In Fig. 2(a), it is clearly observed that as \( 2R_1 \) for the MSF decreased from infinity (straight curve) to 12 mm, the SW-BLE was redshifted, which can be used as a high pass filter (HPF) in the wavelength domain. The variation of the SW-BLE, \( \lambda_c \), with \( R \) has been described as \( \lambda_c \approx 1/\sqrt{R} \) from a simple effective index model [2], which was in a good agreement with our experiment. However, we note in our experiments that there was gradually increasing leakage loss of the flat passband and spectral transmission oscillation near the BLE with reduction of the bending curvature. These are mainly due to the imperfect structure of the MSF and the coupling of the core mode to the whispering-gallery (WG) cladding modes [10]. Bending sensitivity and slope of BLE strongly depend on hole size \( d \), pitch \( \Lambda \), and length of the MSF [3,4]. We expect that the wideband high-pass characteristic can be enhanced with a steeper slope and a flatter passband by optimizing the above MSF waveguide parameters.

HOF was composed of three layers: a central air hole, a GeO\(_2\)–SiO\(_2\) ring-core, and an SiO\(_2\) cladding as shown in Fig. 1 (top right) [6]. The HOF has a distribution of optical field further extended into the cladding region, which makes it a bend-sensitive waveguide. To experimentally quantify the bending-induced BLE shifts of the HOF, we chose a 1 m long HOF with a 4 µm air-hole diameter, a 3 µm ring-core thickness, a 125 µm outer cladding diameter, and a relative core–clad index difference of 0.5%. As in Fig. 2(b), the transmission spectra had steep cutoffs, and they were blueshifted as the bending radius decreased. Note that this is the first experimental report of BLE shift in the HOF. The LW-BLE of the HOF was proportional to the diameter \( 2R_2 \), which closely resembled the bending feature of the W or M profile fibers [11,12]. We, therefore, could experimentally confirm that the bending-induced LW-BLE of the HOF enabled a low-pass optical function in the wavelength domain in contrast to MSF. The BLE shifts in the HOF and the MSF are summarized in Fig. 3(a) as a function of bending radii. The graph

![Fig. 2](image1.png)

**Fig. 2.** (Color online) (a) Transmission spectra of the MSF with a single-turn bend of various bending radii, which shows a high pass characteristic. (b) Transmission spectra of the HOF with a single-turn bend of various bending radii, which shows a low-pass characteristic.

![Fig. 3](image2.png)

**Fig. 3.** (Color online) (a) BLE shifts as a function of bending radius curvatures for the MSF \((1/\sqrt{R})\) and the HOF \((-R)\). (b) Transmission spectra through the proposed composite fiber device for various bending radii, which shows tunable bandpass transmission characteristics.
clearly shows opposite directions of BLE shifts along with different functional dependence, $1/\sqrt{R}$ versus $R$ for the MSF and the HOF, respectively.

To utilize these contrasting BLE shifts in the MSF and the HOF, we concatenated two fibers by fusion splicing them via SMF segments and examined the transmission characteristics of the whole composite structure for various bending conditions. The bending was applied in a circular loop with a single turn of fibers. The spectra summarized in Fig. 3(b) shows unique bandpass transmission characteristics. By changing the bending radii individually ($R_1, R_2$, the width of the passband could be flexibly tuned from 1000 to 300 nm. The center wavelength was located in the range of 1161.8 to 1203.4 nm. The passband showed more than a 20 dB extinction ratio in all cases. The ripple on the passband is attributed to the WG modes of the MSF and can be minimized by designing an optimal MSF structure. In addition, we can easily tune the center wavelength of the transmission by varying the HOF air-hole sizes. The overall insertion loss was in the range of 1–2 dB [13], which is mainly attributed to splice losses between SMF–MSF and SMF–HOF as well as the bending loss itself.

In conclusion, we experimentally demonstrated a novel tunable transmission characteristic in a serially concatenated MSF–HOF composite all-fiber structure. We found that the HOF showed a unique blueshift in the BLE proportional to the bending radius $R$. All the while the MSF showed a redshift proportional to $1/\sqrt{R}$. The distinctive and contrasting shifts in macrobending-induced BLE of the MSF and the HOF provided a unique transmission window bounded by fundamental mode cutoffs. The bandwidth of the window could be widely tuned from 1000 to 300 nm with a high extinction ratio over 20 dB along with a relatively low insertion loss below 2 dB.

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