Compact optical short-pass filters based on microfibers

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We demonstrate a compact short-pass filter fabricated by integrating a microfiber ($\sim 1\ \mu$m in diameter) with a low-index substrate. By varying the interaction length (from 0.65 to 3 mm) between the microfiber and the substrate for wavelength-dependent evanescent leakage, the cutoff wavelength has been tuned over a wide range of 400 nm. Typical rejection loss is higher than 40 dB with insertion loss as low as 0.3 dB. The fiber-diameter-dependent cutoff is also investigated, suggesting that the filter can be applied over a wide spectral range from 600 to 1500 nm. The microfiber-based short-pass filters demonstrated show advantages of compact size, wideband applicability, simple structure, high rejection loss, and compatibility with miniaturized fiber devices. © 2008 Optical Society of America

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Optical fiber filters with low insertion loss and high compatibility with outer fiber systems, which filter out noise or unwanted signals and flatten or suppress gain profile after amplification, are one of the most important optical components in optical fiber networks [1–4]. Short-pass filters, as one of this type, are essential for photonic systems and networks [5–7]. In past years, a variety of fiber short-pass filters have been demonstrated based on dispersive fibers [5,6,8], side-polished fibers with polymer overlay [9], photonic crystal fibers [10], and tapered fibers [11]. Recently, micro-/nanofibers with diameters close to or smaller than the wavelength of the guided light have shown high potential for realization of miniaturized fiber-optic components or devices [12–21]. Although some types of microfiber filters have been realized based on ring resonators [17,18], short-pass filters have not been reported yet. In a recent work, the short-pass filter effect is reported in semiconductor nanoribbons due to substrate-induced leakage [22,23], indicating a possible route to compact short-pass filters based on one-dimensional micro/nanostructures. In this Letter, by integrating a microfiber with a low-index MgF_2 substrate, we present a simple approach to compact short-pass filters covering from the visible to the infrared region. The filters demonstrated here are featured with several advantages, including compact size, easy fabrication, high rejection loss, tunable cutoff wavelength, and wideband applicability.

The proposed short-pass filter is schematically illustrated in Fig. 1(a). A taper-drawn biconical silica microfiber (drawn from SMF-28e, Corning, using a flame-heated taper drawing technique [12,24]), with a uniform waist of about 1 μm in diameter, is placed in close contact with a piece of MgF_2 wafer of about 1 mm in thickness. The thickness of the substrate should not be too thin (e.g., comparable with the wavelength of the light), otherwise periodic transmitted intensity responses (which cannot be adapted for short-pass filtering) may occur as reported in previous works [25,26]. Besides, the surface of the MgF_2 crystal is finely polished and cleaned for tight contact with the microfiber. The whole length of the tapered region (including the uniform waist and conical tapers at both sides) is about 3 cm, and the uniformity of the central part of the taper (defined as $\Delta D/L$, where ΔD is the maximum diameter variation over a length of L) is averaged 5×10^{-5}. The microfiber is attracted to the substrate through van der Waals and electrostatic attractive force. Both sides of the as-drawn microfiber are continuously connected to the standard fibers for light launching and collecting.

In an air-clad micro-/nanofiber with a diameter close to or smaller than the wavelength of the guided light, a certain fraction of power is guided outside the

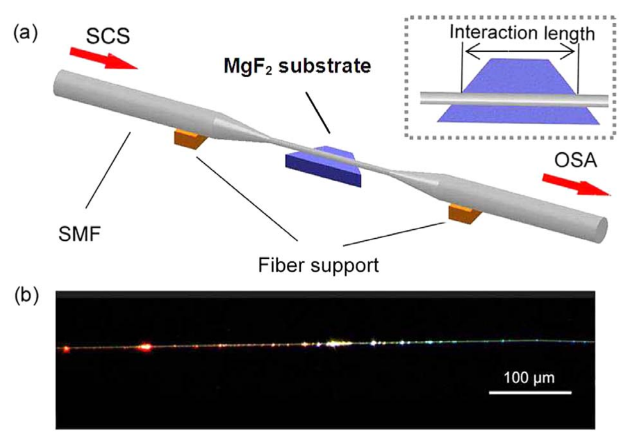

Fig. 1. (Color online) (a) Schematic of the short-pass filter assembled with a MgF_2-substrate-supported microfiber. An SCS is launched into the left-hand side, and the output from the right-hand side is sent to an OSA. Inset, a top view of the contact area of the microfiber and the substrate. (b) Optical microscope image of an MgF_2-supported 1 μm diameter microfiber guiding a supercontinuum light. From the left side to the right side, the color of the scattering light changes from orange to yellow, green, and blue in succession.

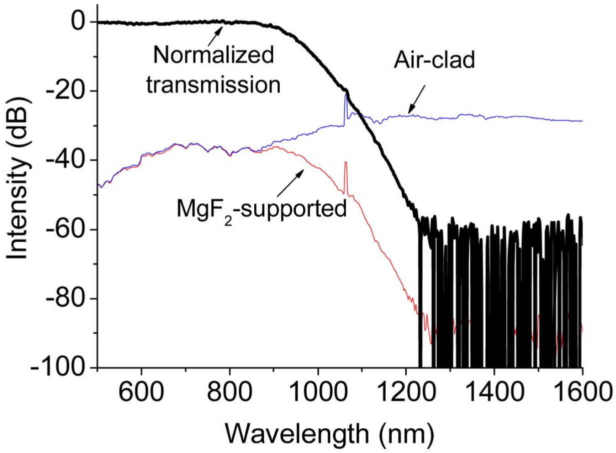

Fig. 2. (Color online) Typical transmission spectra of a short-pass filter. The blue (marked with "Air-clad") and red (marked with "MgF_2-supported") curves represent the output spectra before and after the integration with the substrate, respectively, and the bold black curve represents the normalized transmission. The diameter of the microfiber is 1.04 μm, and the interaction length is 1.1 mm.

fiber as evanescent waves; the longer the wavelength, the larger the fraction of evanescent power, and consequently the lower effective index of the guided mode. When the effective index approaches the index of the substrate, light leaks into the substrate and thus a longer wavelength will be filtered out. Shown in Fig. 1(b) is an optical microscope image of an MgF_2-supported 1 μm diameter microfiber guiding a supercontinuum light. When the supercontinuum light (orange) is launched from the left side, the color of the scattering light (which represents the spectral components of the local guided mode) changes from orange to yellow, green, and finally blue at the right side, clearly showing the short-pass filter effect in the supported microfiber.

To quantify the filtering effect, the transmission spectra of the microfiber short-pass filters have been measured with a supercontinuum source (SCS) (Koheras SuperK Red) and an optical spectrum analyzer (OSA) (Ando model AQ-6315A). Figure 2 shows the typical transmission spectra of the short-pass filter assembled with a 1.04 μm diameter microfiber on a 1.1 mm width MgF_2 substrate. The short-pass effect is clearly shown in the normalized transmission spectrum (bold black curve). For reference, the original outputs from the microfiber before (blue curve, marked with "Air-clad") and after (red curve, marked with "MgF_2-supported") the integration with the substrate are also provided. If we define −30 dB as the criterion of the cutoff intensity, the filter cuts off around 1110 nm. There is no notable optical loss in the passband, namely, the insertion loss is very low. The rejection loss is higher than 50 dB, which is better than those obtained in many other filter structures [6,8,11].

To investigate the possibility of tuning the cutoff wavelengths of the filter, we change the interaction length of the microfiber and the substrate by means of micromanipulation under an optical microscope. In the experiment, a taper-drawn fiber probe is used to shift the microfiber on the surface of the MgF_2 substrate, which is intentionally cut into a trapezoid so that shifting the microfiber relative to the substrate changes the interaction length. Figure 3(a) shows a typical transmission spectra of a filter based on a 0.99 μm diameter microfiber. With the decreasing interaction length from 3 to 0.65 mm, the cutoff wavelength increases from 640 to 1064 nm. Figure 3(b) plots the interaction-length-dependent cutoff wavelength of the filter; the monotonous and near-linear dependence over a 400 nm span indicates the possibility for wideband tuning of the cutoff wavelength.

With a given interaction length, the cutoff wavelength is also strongly dependent on the diameter of the microfiber. As the fiber diameter decreases, the effective index of guided modes in the microfiber decreases, resulting in a blueshift of the cutoff wavelength. Figure 4 characterizes the microfiber-diameter dependence of the filter effect. While the interaction length is kept at 1.1 mm, the diameter of the microfiber is changed from 0.75 to 1.96 μm. Figure 4(a) gives normalized transmission spectra with microfiber diameters of 0.75, 0.88, 1.17, 1.29, 1.42, 1.72, 1.82, and 1.96 μm, respectively. Excellent short-pass filter effects are observed with a cutoff wavelength ranging from 570 to 1480 nm. Figure 4(b)

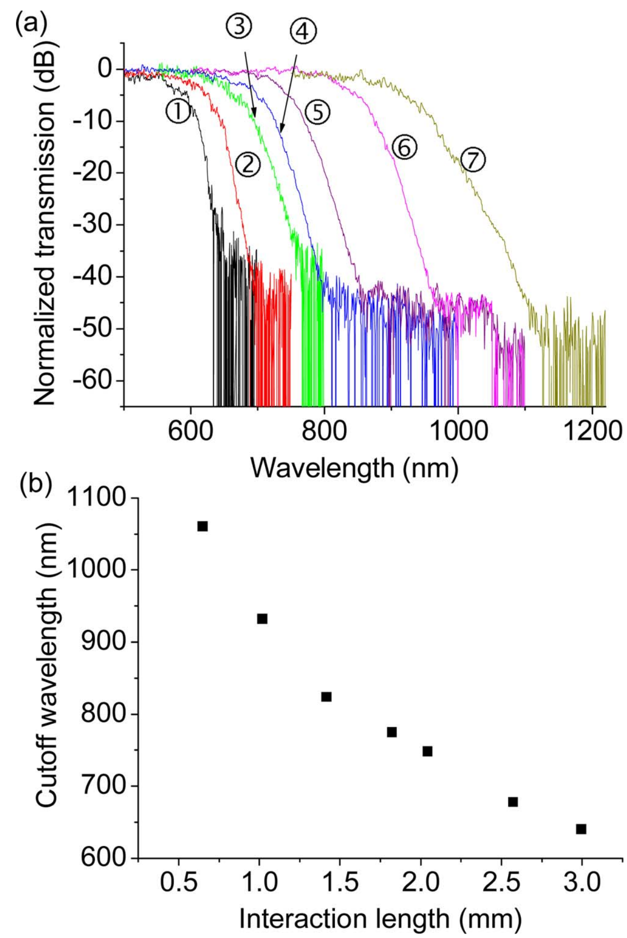

Fig. 3. (Color online) (a) Normalized transmission spectra of a microfiber-assembled short-pass fiter with interaction lengths of ①, 2.99; ②, 2.57; ③, 2.04; ④, 1.82; ⑤, 1.42; ⑥, 1.02; and ⑦, 0.65 mm. The diameter of the microfiber is 0.99 μm. (b) Cutoff wavelength versus interaction length.

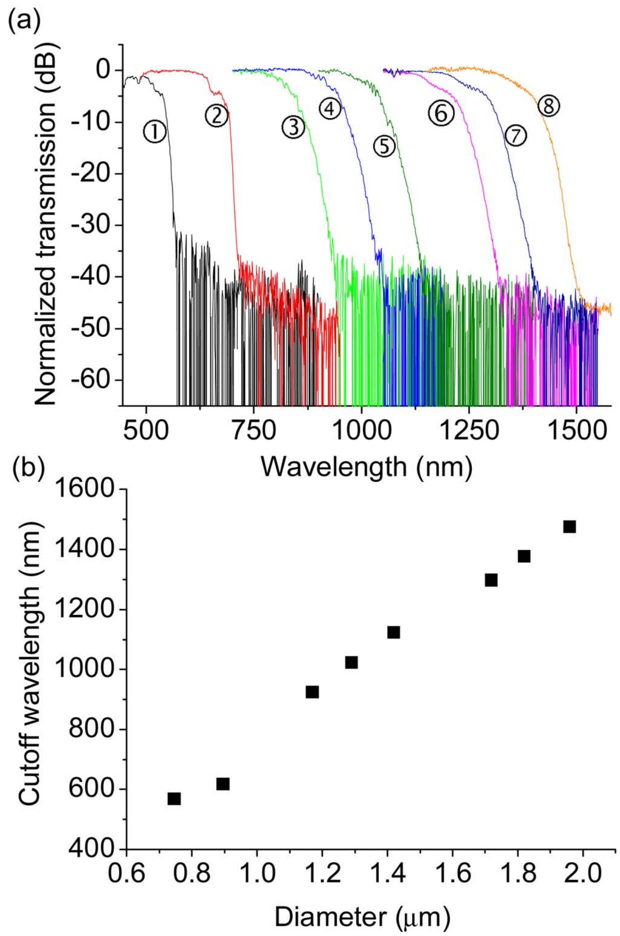

Fig. 4. (Color online) (a) Normalized transmission spectra of microfiber-based short-pass filters with microfiber diameters of ①, 0.75; ②, 0.88; ③, 1.17; ④, 1.29; ⑤, 1.42; ⑥, 1.72; ⑦, 1.82; and ⑧, 1.96 μm. The interaction length is predetermined to be 1.1 mm. (b) Cutoff wavelength versus microfiber diameter.

plots the cutoff wavelength with respect to the microfiber diameter, showing a monotonous and near linear dependence, which may be helpful for predicting the cutoff wavelength from the microfiber diameter over a wide spectral range. In addition, the spectral range used here is limited by the available working ranges of the light source and the optical spectrum analyzer. Considering that the transparent bands of both the fiber material (silica) and the substrate (MgF_2) are much broader, the filter demonstrated here can be applied to a much broader spectral range.

In conclusion, we have experimentally demonstrated a compact optical short-pass filter assembled with a low-index-substrate-supported microfiber. A wide tuning range over 400 nm is achieved by varying the interaction length between the microfiber and the substrate. An investigation of the microfiber-diameter dependence shows that the filter can be well-adapted within visible and near-infrared spectral ranges with an appropriate microfiber diameter. Compared with previously reported structures [8–11], the filter demonstrated in this Letter is very compact and simple in structure with favorable properties including wideband applicability, high rejection loss, and compatibility with miniaturized fiber devices and may find applications in wideband photonic circuits or devices with high compactness.

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