Bandpass Filter With Variable Bandwidth Based on a Tapered Fiber With External Polymer Cladding

Kuei-Chu Hsu, Nan-Kuang Chen, Sen-Yih Chou, Shien-Kuei Liaw, Yinchieh Lai, and Sien Chi

***Abstract*—A thermo-optical bandwidth-variable fiber-based bandpass filter is experimentally and theoretically demonstrated by simply utilizing a tapered standard single-mode fiber covered with a dispersive polymer layer. The 3-dB spectral bandwidth can be tuned from 250 to 500 nm with the filter center wavelength around 1 μm.**

***Index Terms*—Optical fiber components, optical fiber filters, optical fibers.**

I. INTRODUCTION

FIBER-BASED filters have attracted considerable research interest due to their compact size and low insertion loss for fiber-optic applications. With the existing technologies, bandpass fiber-based optical filters provide different bandwidths ranging from $\leq$1 to $\geq$100 nm. Among different bandwidth applications, wide-bandwidth tunable bandpass filters are very effective for spectra-shaping in some super-wideband light sources. This wide-bandwidth spectra-shaping capability is generally required by optical coherence tomographic applications. A center wavelength near the 1-μm eye-safe wavelength region and wide-bandwidth apodized spectra are required to achieve excellent imaging quality [1], [2]. Several design and fabrication methods have been developed to achieve wide operation bandwidths. These methods include approaches that utilize long-period fiber gratings inscribed on unique fibers, or utilize complex photonic bandgap fibers [3]–[5]. However, some particular filtering functions such as filter bandwidth tunability and apodized spectral shaping remain difficult to achieve without using complex design and manufacturing techniques.

This work presents a novel and simple wideband and bandwidth-variable bandpass fiber filter using a tapered standard single-mode fiber covered with a thick dispersive polymer layer around its uniform waist. Our previous study described the short-wavelength-pass spectral characteristics by surrounding the tapered fibers with Cargille liquids [6]. In principle, other optical materials, such as optical glass or optical polymers, can also be utilized to engineer filter dispersion for practical applications. In this work, optical polymer OCK-433 (Nye Lubricants) is used to cover tapered fibers as external cladding. Compared with known short-wavelength-pass filters composed of a side-polished fiber covered with optical polymers [7], novel bandpass phenomena are observed for this proposed fiber filters due to the use of appropriate material and waveguide dispersion effects. To obtain bandpass filtering, both the fundamental-mode cut-on and cut-off mechanisms must be generated by carefully engineering material and waveguide dispersion. The passband of the proposed fiber filter is roughly defined by the two cross points of the refractive index dispersion (RID) curves for the dispersive polymer and tapered fiber. By tapering the standard single-mode fibers, this work demonstrates experimentally that filter bandwidth can be thermo-optically tuned with a 3-dB spectral bandwidth of 250–500 nm. Numerical simulation using the beam propagation method (BPM) was applied to investigate dispersion engineering effects and determine the optimal diameter of the tapered fiber for attaining optimal bandpass performance.

II. DEVICE STRUCTURE AND FABRICATION

The bandpass fiber filter with thermo-optic tunable bandwidth is achieved by tapering a standard telecommunication single-mode fiber (SMF-28) and imbedding this fiber inside the thermo-cured dispersive polymer (OCK-433). Tapered fibers are fabricated using the hydrogen flame-brushing technique to achieve a uniform waist. Fig. 1(a) displays the bandpass fiber filter structure. Total elongation length of the tapered fiber is around 4.5 cm and uniform waist length is approximately 1 cm. The diameter ρ of the uniform waist can be controlled by tuning experimental parameters during the tapering procedure. The OCK-433 polymer with a thermo-optical coefficient of $dn_D/dT = -3.2 \times 10^{-4}$ °C is applied to cover the tapered fiber, which is then cured thermally. Fig. 1(b) shows the RID curves of the Ge-doped core, pure silica, and the dispersive polymer OCK-433 at different temperatures. The two points at which the curves of pure silica and the dispersive polymer cross roughly define the fiber filter passband. This is when light is guided inside the fiber, the refractive index of the external cladding cannot exceed the refractive index of the waveguide.

Manuscript received January 21, 2009; revised March 06, 2009. First published April 21, 2009; current version published June 17, 2009. This work was supported by the National Science Council of the Republic of China (NSC 96-2221-E-009-128-MY3, NSC-97-2923-E-011-001-MY3, and NSC-97-2219-E-011-004).

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Digital Object Identifier 10.1109/LPT.2009.2020806

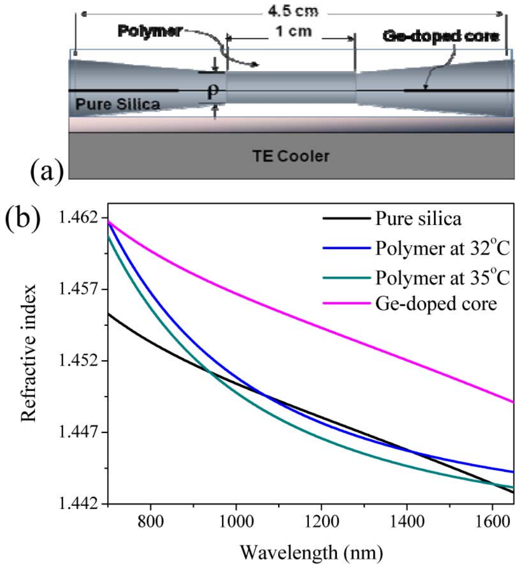

Fig. 1. (a) Diagram of a tapered optical fiber structure with a uniform waist coated by dispersive polymer. (b) RID curves of the core and cladding of SMF-28 and the dispersive polymer.

Because germanium dopant in the core will diffuse into the original cladding during the tapering process, the effective RID curve of the tapered fiber without the polymer will be located between those of the original core and original cladding. A thermoelectric cooler is used to control polymer temperature and thereby change its refractive index for tuning the cut-on and cut-off wavelengths. The fundamental-mode cut-on and cut-off wavelengths can be tuned upward or downward using the thermo-optical coefficient (dn_D/dT) of the dispersive polymer materials and applied heating temperature. According to the RID curves in Fig. 1(b), increasing the temperature of the fiber filter increases bandwidth, and the passband can be tuned over hundreds of nanometers.

III. MEASUREMENTS AND SIMULATIONS

A halogen lamp source is used as the light source when measuring the cut-on and cut-off spectral response of the fabricated filter; transmission spectra are recorded by an optical spectrum analyzer. For experimental demonstration, another suitable bare tapered fiber is connected before this fiber filter and acts as a spatial mode filter that filters out high-order fiber modes to ensure that only the fundamental mode input exists at wavelengths of interest. For practical devices, true single-mode fibers at operating wavelengths must be utilized to avoid input excitation of high-order modes. Fig. 2(a) and (b) shows the experimental spectral responses of the tunable bandpass fiber filter for $\rho = 22$ and 14 μm at different temperatures, respectively. The index difference between the tapered fiber and dispersive polymer at high temperatures is larger than that at the low wavelength; thus, the optical fields are strongly guided inside the passband, generatng a flat-top spectral shape. Conversely, the filter at the low temperature creates a nonflat-top spectral profile and generates relatively higher losses inside the passband. The 3-dB bandwidth at 39 °C is around 400 nm with an insertion loss of $\leq$0.5 dB for the $\rho = 22\ \mu$m tapered diameter. At 35 °C the spectral response has an apodized shape with a 3-dB bandwidth around 250 nm and insertion loss is around 2.5 dB [Fig. 2(a)]. Insertion loss can result from tapering transformation and absorption/scattering of the polymer cladding. When near cut-off, the latter origin depends on the index difference between the fiber and polymer resulting from the corresponding change in mode filed diameter. When temperature decreases, the guided mode is close to the cut-off and thus insertion loss increases. The central wavelengths of the passband differ at different temperatures. This is attributed to the asymmetrical shifts of the cut-on and cut-off wavelengths when temperature varies.

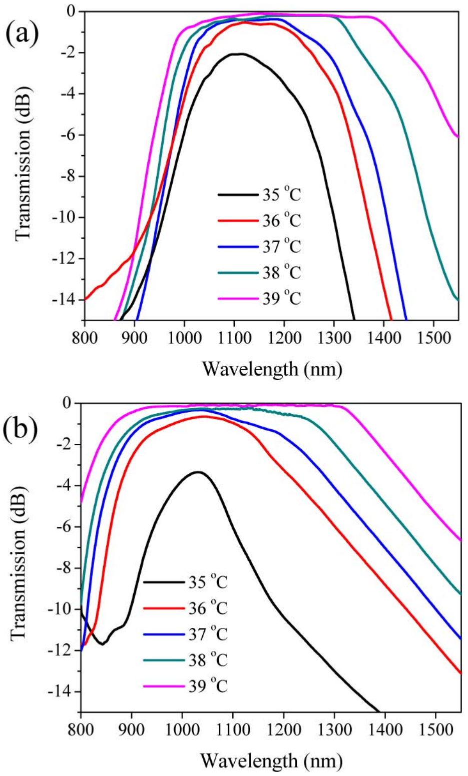

Fig. 2. Experimental spectral responses of the tunable bandpass fiber filter for (a) $\rho = 22\ \mu$m and (b) $\rho = 14\ \mu$m at different temperatures. (Resolution: 5 nm.)

The effect of the polymer on the tapering transformation region should be small for the following reasons. First, the effective length of polymer coverage is very small. Thus only the end portion of the tapering transformation region where the guided mode can penetrate the polymer cladding contributes to this effect. Second, a large fiber diameter will have a large transmission bandwidth (Fig. 3). Therefore, the filtering ability of the device is primarily determined by the flat middle region where fiber diameter is smallest. The operational center wavelength of the filter is located near 1 μm and is principally determined by dispersion properties of the fiber and cladding material (polymer), as illustrated in Fig. 1(b). In principle, further center wavelength tunability should be achievable by using fiber structures with increased temperature and wavelength sensitivities of cladding materials/meta-materials.

To assess the fundamental-mode cut-on and cut-off characteristics in relation to waveguide dispersion effects, the BPM algorithm is used to numerically simulate optical field propagation effects within tapered fibers covered by the dispersive

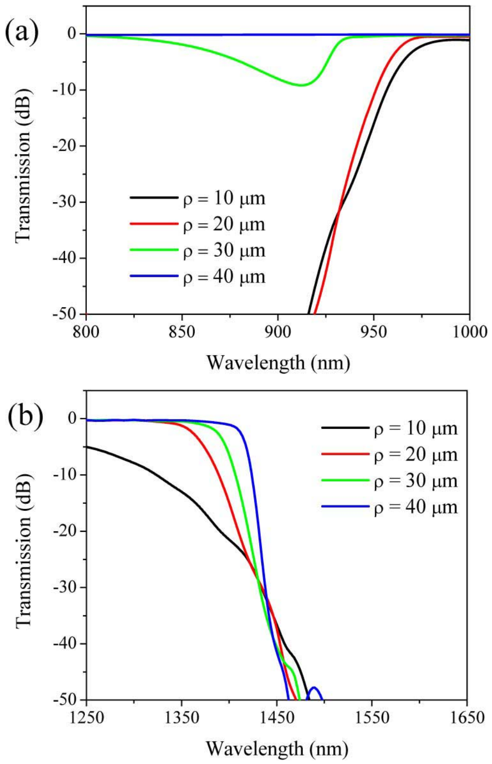

Fig. 3. Simulation results of transmission spectra at different waist diameters of 10, 20, 30, and 40 μm for spectral range at (a) 800–1000 nm, (b) 1250–1650 nm.

polymer. Simulation details for the tapered (short-pass) fiber filters are described in [8]. We assume input light is the fundamental fiber mode and the transition region has a smooth exponential shape, ensuring smooth mode transformation. Individual wavelengths are simulated sequentially to calculate transmission spectra. Fig. 3(a) and (b) shows simulated loss spectra assuming fundamental mode input with fiber taper diameters of 10, 20, 30, and 40 μm. Fiber transition length is 1.8 mm, uniform waist length is 10 mm, and temperature is 35 °C. Both cut-on and cut-off spectral responses exhibit the following tendency: when waist diameter increases, band-edge steepens. However, since the optical fields at short wavelengths are confined tighter than those of the long wavelength, when taper diameter exceeds 30 μm, bandpass phenomena disappear and the device becomes a short-wavelength pass filter as previously reported [6]–[8]. These simulation results are in reasonable agreement with experimental data. In particular, these results theoretically confirm the possibility of achieving bandpass filtering via the proposed mechanism. Based on simulation results, optimal bandpass operation of the filter with a flat-top spectral shape occurs when the tapered fiber diameter is around 20 μm.

IV. CONCLUSION

This work demonstrates experimentally and theoretically the feasibility of a novel fiber-based bandpass optical filter with an ultrawide and variable spectral bandwidth. This thermo-optic bandwidth-variable filter is fabricated using a tapered standard single-mode fiber covered with a dispersive polymer around the tapered waist, thus forming the passband via appropriate dispersion engineering design. By suitably adjusting material and waveguide dispersion, bandpass fiber filters can generate a flat-top spectral passband in such a manner that the spectral width of the passband can be tuned from 250 to 500 nm, with a filter center wavelength of roughly 1 μm. Due to its simple fabrication procedure and thermo-optical tunability, the proposed fiber-based filter is very cost-effective and promising for practical use.

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