New in-line fiber band pass filters using high silica dispersive optical fibers

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Abstract

New types of in-line fiber filters whose core and cladding are composed of binary silica doped with either boron or fluorine are proposed. Utilizing dispersive characteristics of SiO$_2$–B$_2$O$_3$ and SiO$_2$–F systems, we demonstrate that an optical fiber, with borosilicate core and fluorosilicate cladding, shows short-pass filter response. Experimentally, we fabricated a short-pass filter fiber that could be used as a 1310/1550 nm WDM filter. We also propose theoretically that a long-pass filter could be obtained in a fiber structure whose core is fluorosilicate with borosilicate cladding. In a special long-pass filter structure, we found that the normalized frequency can be kept uniform over a wide wavelength range from 1200 to 1700 nm, which will be applied in wideband wavelength division multiplexing devices. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

With rapid growth of wavelength division multiplexing (WDM) optical communication systems, various fiber filters are being intensively developed to manipulate optical channels in the spectral domain. Fiber-based filters have drawn attention due to their low insertion loss, low cost, and flexible design in spectral responses. Currently, fiber filters based on the mode coupling mechanism are being deployed in communication systems. Among those, fiber Bragg gratings (FBGs) [1] and fiber long-period gratings (LPGs) [2] are well-established technologies, where the spectral responses could be tailored by control of the mode coupling defined by the fiber waveguides and refractive index grating structures inscribed by UV exposure. Fiber acousto-optic tunable filter (AOTF) [3] is another type of fiber filter based on the mode coupling, which induced by a tunable flexural acoustic wave along the optical fiber. Bandwidths of these fiber filters, however, are limited by the phase matching conditions and the overlap integrals between the coupled modes.
Morishita et al. [4,5] reported a different class of broadband fiber filters by using highly dispersive characteristics of the core and the cladding made of multi-component glasses (MCG). In the devices, two different types of glasses whose dispersion curves, refractive index versus wavelength, cross each other are used for the core and the cladding, so that the refractive index difference between them could change as shown in Fig. 1. Those dispersive fibers could inherently function as either a short-pass or a long-pass filter depending on the glass composition of the waveguides. Despite their simple structures, dispersive MCG fibers have not been readily applicable to practical optical communications and sensor systems due to fundamental problems in splicing with conventional single mode fibers (SMFs). First of all, dispersive MCG fiber could not be fusion spliced to SMF using conventional electric arc technologies due to the large differences in melting points and thermal expansion coefficients between MCG and high silica in SMF. Although mechanical butt-coupling might be attempted between those glasses, it induces a large insertion loss due to the mismatch in refractive indices and subsequent Fresnel reflection loss. Furthermore, MCG dispersive fibers suffer from a large scattering loss because they are fabricated by rod-in-tube (RIT) technique that tend to induce irregularities and imperfections at the core-cladding interface.

In this paper, we propose a new dispersive optical fiber made of high silica that is compatible to conventional SMF. Highly dispersive characteristics of fiber were obtained by using borosilicate glass and fluorosilicate glass as its constituents [6,7]. This fiber can be fabricated using conventional vapor precursors such as BCl3 and SiF4 along with modified chemical vapor deposition (MCVD) system that would significantly reduce the fiber attenuation and fusion splice loss with SMFs. Spectral responses of the proposed fiber were theoretically analyzed and a short-pass filter fiber was experimentally demonstrated.

![Fig. 1. Principle of dispersive fiber filters based on two glasses whose dispersion curves cross each other. Note that depending upon the choice of core and cladding compositions, the fibers could function as either short-pass or long-pass filters.](image-url)
2. Dispersive characteristics of B\textsubscript{2}O\textsubscript{3}–SiO\textsubscript{2} and FSiO\textsubscript{2} glass systems

The dispersive characteristics of binary silica glass that is doped with dopants such as GeO\textsubscript{2}, P\textsubscript{2}O\textsubscript{5}, F and B\textsubscript{2}O\textsubscript{3} have been precisely calculated using the Sellmeier equation for given ranges of concentrations. Sellmeier equation \[8\] for the refractive index \( n_j \) is given as

\[
 n_j^2(\lambda) - 1 = \sum_{i=1}^{3} \frac{a_{ij}\lambda^2}{\lambda^2 - l_{ij}}, \quad (1)
\]

where the suffix \( j \) refers to the concentration of dopants, and \( \lambda \) is the optical wavelength in \( \mu \text{m} \). Sellmeier coefficients, denoted by \( a_{ij} \) and \( l_{ij} \), for binary silica doped with F and B\textsubscript{2}O\textsubscript{3} \[8\] are summarized in Table 1. In general, refractive indices of binary silica glasses decrease monotonically with the wavelength. B\textsubscript{2}O\textsubscript{3} shows a unique dispersion slope, \( dn/d\lambda \), such that its dispersion curve, \( n(\lambda) \), could cross those of other dopants, which is the fundamental principle of the dispersive fiber initially proposed by Morishita et al. \[4,5\]. The matching dopant of B\textsubscript{2}O\textsubscript{3} was found to be F to make a dispersive waveguide in the wavelength region for optical communications. The dispersion curves of SiO\textsubscript{2}–B\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2}–F glasses are shown in Fig. 2. The cross-wavelength, \( \lambda_c \), where dispersion curves of the two glasses cross each other, is around 1.12 \( \mu \text{m} \) for binary silica glasses doped with 1.796 mol.% of fluorine and 6.830 mol.% of B\textsubscript{2}O\textsubscript{3}. The index difference between the two glasses increases as the wavelength moves away from reaching 0.0005 near 0.8 and 1.5 \( \mu \text{m} \), which is about 1/10 of that of conventional SMFs. Even though the index differences are relatively small, the core diameter could be increased to make a waveguide sufficient enough to function as a band pass filter and experimental results are discussed in the following section.

In previous MCG dispersive fibers, the cross-wavelengths were adjusted by post-annealing process \[5\] for the given pair of glass compositions of the core and the cladding. In these SiO\textsubscript{2}–B\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2}–F glass systems, however, very fine adjustment of the cross-wavelength could be achieved by controlling the flow rate of precursors such as BCl\textsubscript{3}, SiF\textsubscript{4} in MCVD process. Sellmeier parameters for the SiO\textsubscript{2}–B\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2}–F glass systems have been given for relatively low concentration ranges, which allow us to linearly interpolate the parameters for an arbitrary concentration within the ranges. Fig. 3 shows the routine for decision of concentrations of B\textsubscript{2}O\textsubscript{3} and F in order to obtain a desired cross-wavelength. For the first step, refractive index differences of the core (\( \Delta n_{co} \)) and the cladding (\( \Delta n_{cl} \)) at 0.6328 \( \mu \text{m} \), referenced to pure silica, are assumed for a given cross-wavelength. Then the corresponding dopant concentrations are obtained from the interpolation of Sellmeier coefficients for SiO\textsubscript{2}–B\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2}–F glass systems given in Table 1. With these coefficients, the refractive index curves of the core and the cladding are plotted to check whether the cross-wavelength is in the valid spectral range. This process is repeated until the cross-wavelength meets the desired value.

A short-pass filter can be made by choosing SiO\textsubscript{2}–B\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2}–F as the core and the cladding, respectively \[6\]. As an example, in 1.3/1.5 \( \mu \text{m} \)

<table>
<thead>
<tr>
<th>mol.%</th>
<th>SiO\textsubscript{2}</th>
<th>B\textsubscript{2}O\textsubscript{3}</th>
<th>F</th>
<th>( a_1 )</th>
<th>( l_1 )</th>
<th>( a_2 )</th>
<th>( l_2 )</th>
<th>( a_3 )</th>
<th>( l_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.6961663</td>
<td>0.004679148</td>
<td></td>
<td>0.4079426</td>
<td>0.01351206</td>
<td>0.8974994</td>
<td>97.934002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>97.0</td>
<td>0.6935408</td>
<td>0.005141195</td>
<td></td>
<td>0.4052977</td>
<td>0.01578530</td>
<td>0.9111432</td>
<td>97.93387</td>
<td></td>
<td></td>
</tr>
<tr>
<td>96.5</td>
<td>0.6929642</td>
<td>0.003658351</td>
<td></td>
<td>0.4047468</td>
<td>0.01536631</td>
<td>0.9154064</td>
<td>97.93383</td>
<td></td>
<td></td>
</tr>
<tr>
<td>86.7</td>
<td>0.690618</td>
<td>0.00383161</td>
<td></td>
<td>0.401996</td>
<td>0.01529229</td>
<td>0.898817</td>
<td>82.79107308</td>
<td></td>
<td></td>
</tr>
<tr>
<td>96.9</td>
<td>0.69325</td>
<td>0.004521218</td>
<td></td>
<td>0.39720</td>
<td>0.01372178</td>
<td>0.86008</td>
<td>95.57213121</td>
<td></td>
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</tr>
<tr>
<td>93.9</td>
<td>0.67744</td>
<td>0.003763823</td>
<td></td>
<td>0.40101</td>
<td>0.01447209</td>
<td>0.87193</td>
<td>97.14664969</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The coefficients are valid for spectral range of 0.4–1.7 \( \mu \text{m} \).
The WDM application the cross-wavelength was chosen as 1.40 µm and the dopant concentrations were estimated as 6.22 mol.% of B\(_2\)O\(_3\) and 1.86 mol.% of F in fused silica using the Sellmeier interpolation routine described above. The dispersion curves for the given dopant concentrations are shown in Fig. 4. The refractive index difference between the core and the cladding monotonically decreases with the wavelength to the cross-wavelength 1.40 µm, over which the core index is lower than the cladding. Therefore, the dispersive fiber will guide only the light whose wavelength is shorter than the cross-wavelength to function as a short-pass filter. The effects of dopant concentrations on the cross-wavelength were analyzed in Figs. 5(a) and (b). If the B\(_2\)O\(_3\) concentration increases from 6.22 to 7.74 mol.% for the fixed fluorine concentration of 1.86 mol.%, \(\lambda_c\) decreases from 1.40 to 0.97 µm. On the other hand, the cross-wavelength increases to 1.68 µm when the fluorine concentration increases from 1.86 to 2.05 mol.% for the fixed B\(_2\)O\(_3\) concentration of 6.22 mol.%. It is, therefore, found that in a short-pass fiber composed of SiO\(_2\)–B\(_2\)O\(_3\) core and SiO\(_2\)–F cladding, boron decreases the cross-wavelength while fluorine increases.

Using the same SiO\(_2\)–B\(_2\)O\(_3\) and SiO\(_2\)–F glass systems, long-pass filters can be also made by choosing SiO\(_2\)–F and SiO\(_2\)–B\(_2\)O\(_3\) as the core and the cladding, respectively. As an example of applications, dispersion curves of the core doped with 2.01 mol.% of F and the cladding doped with 9.96 mol.% of B\(_2\)O\(_3\) are shown in Fig. 6. Here the cross-wavelength was estimated to be around 0.68 µm. In the same manner as in short-pass filters, the dispersion curves of borosilicate and fluorosilicate glasses for a short wavelength-pass fiber with the cross-wavelength at 1.40 µm. Note that dopant concentrations are 6.22 mol.% of B\(_2\)O\(_3\) and 1.86 mol.% of fluorine in SiO\(_2\).
cross-wavelength can be adjusted by dopant concentrations. The effects of dopant concentrations on the cross-wavelength are analyzed in Fig. 7(a) and (b). As the B$_2$O$_3$ concentration decreases from 9.96 to 7.74 mol.% for the fixed fluorine concentration of 2.01 mol.%, $\lambda_c$ increases from 0.68 to 1.16 $\mu$m. On the other hand, the cross-wavelength increases to 1.12 $\mu$m when the fluorine concentration increases to 2.44 mol.% for the fixed B$_2$O$_3$ concentration of 6.22 mol.%. It is, therefore, found that in a long-pass fiber composed of SiO$_2$–F core and SiO$_2$–B$_2$O$_3$ cladding, boron decreases the cross-wavelength while F increases, which is similar to the case of short-pass filter fibers.

Fig. 5. The effects of dopant concentrations on the cross-wavelength shift: (a) cross-wavelength decreases from $\lambda_{c1}$ (1.40 $\mu$m) to $\lambda_{c2}$ (0.97 $\mu$m) when the B$_2$O$_3$ concentration increases from 6.22 to 7.74 mol.% for the fixed fluorine concentration of 1.86 mol.%; (b) cross-wavelength increases from $\lambda_{c1}$ (1.40 $\mu$m) to $\lambda_{c3}$ (1.68 $\mu$m) when the fluorine concentration increases from 1.86 to 2.05 mol.% for the fixed B$_2$O$_3$ concentration of 6.22 mol.%.

Fig. 6. The dispersive characteristics for long wavelength-pass fiber. Expected cross-wavelength was 0.68 $\mu$m. Corresponding concentrations were F 2.01 mol.% and B$_2$O$_3$ 9.96 mol.% in SiO$_2$.

Fig. 7. The effects of dopant concentrations on the cross-wavelength: (a) cross-wavelength increases from $\lambda_{c1}$ (0.68 $\mu$m) to $\lambda_{c2}$ (1.16 $\mu$m) when the B$_2$O$_3$ concentration decreases from 9.96 to 7.74 mol.% for the fixed fluorine concentration of 2.01 mol.%; (b) cross-wavelength increases from $\lambda_{c1}$ (0.68 $\mu$m) to $\lambda_{c3}$ (1.12 $\mu$m) when the fluorine concentration increases from 2.01 to 2.44 mol.% for the fixed B$_2$O$_3$ concentration of 9.96 mol.%.
3. Results and discussions

In order to implement the proposed short-pass filter in silica optical fiber, a preform was fabricated using MCVD system. Flow of BCl₃ and SiF₄ vapors were added with precise control along with SiCl₄ during deposition of the core and the cladding layers, respectively. The final preform consisted of three layers, pure silica substrate, F-doped silica inner cladding, and B₂O₃-doped silica core. The refractive index profile measured at 0.6328 μm is shown in Fig. 8. The relative index difference, Δ was 0.085% and the ratio of cladding diameter to core diameter was over 10. The diameter ratio was deliberately chosen over 10 in order to keep the light field guided by the core within the F-doped silica inner cladding minimizing the power leakage to the outer pure silica substrate. From the refractive index, dopant concentrations in the core and cladding were estimated as 10.26 mol.% of B₂O₃ and 2.79 mol.% of F, respectively. The cross-wavelength of the short-pass filter was estimated as 1.42 μm. The preform was then immersed in HF acid solution to etch away the substrate glass to an appropriate diameter. Finally optical fiber was drawn in conventional draw tower. The core and the cladding diameters were 10 and 125 μm, respectively.

Transmission spectra were measured for the short-pass fiber of 40 cm long using a white light source and an optical spectrum analyzer for various bending radii and the results are shown in Fig. 9. The transmission spectrum of conventional fiber in Fig. 9 is inserted to show the insertion loss of silica dispersive fiber. In a straight silica dispersive fiber, signal below 1.0 μm is guided through the core with a low loss, while the signal between 1.2 and 1.4 μm suffers a gradual increase of attenuation. Note that this attenuation results from the dispersive characteristics of the SiO₂–B₂O₃ and SiO₂–F glass systems described in Section 2. More than 25 dB of band rejection efficiency between 1.3 and 1.5 μm was achieved, which makes this fiber an in-line short-pass filter applicable in 1.3/1.5 μm WDM devices. The spectral response of the fiber to macro-bending was also investigated in Fig. 9. The wavelength where the gradual attenuation starts, shifts toward a shorter wavelength as the bending radius decreases. This is a typical characteristic of short-pass filters similar to MCG dispersive fibers [4,5].

The transmission loss of the dispersive fiber is measured as 3.75 dB/m at wavelength of 1.14 μm using cut-back method. This high transmission loss results from very low index difference between the core and cladding of the silica dispersive fiber as well as Rayleigh scattering at short wavelength. According to Fig. 9, the insertion loss of the fiber...
is about 2.1 dB for 40 cm straight fiber at 1.14 μm wavelength, which is mainly attributed weak
guidance of the proposed fiber. Splice loss to conventional single mode optical fiber, Corning
SMF-28, is less than 0.3 dB using conventional fusion splicing equipment without adjustment of
arc conditions. Therefore, silica dispersive fiber can be easily spliced with conventional single mode
fibers but the transmission loss of silica dispersive fiber is large comparing with the MCG dispersive
fibers whose transmission loss is 2–3 dB/m [9,10].

In long-pass filter configurations in Figs. 6 and 7, note that the index difference between the core
and cladding increases for longer wavelengths. This unique dispersive property of long-pass filter
fibers could be used in noble WDM devices as well as band pass filters. Normalized frequency, $V$, of a
cylindrical optical fiber with a step index core is given by

$$V = \frac{2\pi}{\lambda} a \sqrt{n_{co}^2 - n_{cl}^2},$$  \hspace{1cm} (2)

where $a$ is the core radius of, $\lambda$ is the optical wavelength in vacuum, $n_{co}$ and $n_{cl}$ are the refractive
indices of core and cladding, respectively. In conventional SMFs, the $V$ number monotonically
decreases for longer wavelengths resulting in poor mode confinement. In dispersive long-pass filter
fibers, however, the index difference grows with wavelength, which could compensate the $1/\lambda$
dependence of $V$ number in Eq. (2). Taking the dispersion curves in Fig. 6 into Eq. (2), the normal-
ized frequency of a long-pass filter fiber was obtained as a function of wavelength in Fig. 10. The $V$
number shows almost constant value of 1.1 above 1.2 μm, which can be applied in wavelength
insensitive couplers [4,5]. In polished type couplers, cladding region of two fibers is polished
away to bring the cores in close proximity with an index matching liquid interface. A theoretical
analysis of this type of coupler can be found in [11], where the transmitted power $P_t$ and the cou-
pled power $P_c$ are given by

$$P_t = P_0 \cos^2 C_0 L_c,$$
$$P_c = P_0 \sin^2 C_0 L_c,$$  \hspace{1cm} (3)

where $C_0$ represents the coupling strength and $L_c$ is the effective interaction length.
respectively. The coupled power was calculated in the range of 1.2–1.7 μm and the results are shown in Fig. 11. Note that the coupled power is very uniform over the wide wavelength range from 1.2 to 1.7 μm in the coupler made of long-pass fiber. This property could be utilized as wavelength insensitive power splitters or combiner in wideband WDM systems.

4. Conclusions

Utilizing dispersive characteristics of SiO$_2$–B$_2$O$_3$ and SiO$_2$–F glass system, in-line band pass filters were theoretically proposed and demonstrated. It is found that a short-pass filter could be achieved by the structure of SiO$_2$–B$_2$O$_3$ core and SiO$_2$–F cladding, while a long-pass filter with SiO$_2$–F core and SiO$_2$–B$_2$O$_3$ cladding. Precise adjustment of the cross-wavelength can be controlled by dopant concentrations during fabrication procedure. In experiment a short-pass filter with 25 dB band rejection efficiency was fabricated out of 40 cm long fiber with 10.26 mol.% of B$_2$O$_3$ in the core and 2.79 mol.% of F in the cladding, which can be used in 1.3/1.5 μm WDM devices. Transmission loss of silica dispersive fiber was 3.75 dB/m at the wavelength of 1.14 μm and 0.3 dB splicing loss was obtained during splicing with conventional single mode fibers. Uniform guiding property with a constant $V$ number of 1.1 was also theoretically predicted in 1.2–1.7 μm in a long-pass filter whose core has 2.01 mol.% of F and 9.96 mol.% of B$_2$O$_3$ in the cladding and wideband wavelength insensitive couplers performance was predicted.

References