Ultra-wide bandpass filter based on long-period fiber gratings and the evanescent field coupling between two fibers

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Abstract: We demonstrate a fiber-based bandpass filter with an ultra-wide spectral bandwidth. The ultra-wide band feature is achieved by inscribing a long-period fiber grating (LPG) in a specially-designed low index core single mode fiber. To get the bandpass function, the evanescent field coupling between two attached fibers is utilized. By applying strain, the spectral shape of the pass-band is adjusted to flat-top and Gaussian shapes. For the flat-top case, the bandwidth is obtained ~ 160 nm with an insertion loss of ~ 2 dB. With strain, the spectral shape is switched into a Gaussian one, which has ~ 120 nm FWHM and ~ 4.18 dB insertion loss at the peak.

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1. Introduction

Long-period fiber grating (LPG) has been widely studied as a various wavelength-selective device owing to its desirable properties such as easy-fabrication, low insertion loss, low back reflection, and high isolation [1, 2]. One of the most important generic properties of an LPG-assisted device is its capability of providing both band-rejection and band-pass functions, which enables to implement an all-fiber spectral filter for a fiber amplifier, optical sensor, and WDM (Wavelength Division Multiplexing) optical communication system [3-5].

To get a wide operation bandwidth of an LPG-assisted device, several methods have been reported [6-9]. In Ref. [6], by utilizing the dispersion characteristics of a few-mode fiber, a 63 nm bandwidth was achieved with a 20 dB coupling strength. Unlike the rather linear dispersions of the low order cladding modes of a conventional single mode fiber, the modes of a few-mode fiber had parabolic dispersion properties, which allowed having the mode coupling over a wide wavelength range. In Ref. [7], a wide bandwidth of ~ 100 nm was also obtained by using the higher order cladding modes of a conventional single mode fiber. However, it seems that the coupling strength of the LPG is not good enough for the practical application such a spectral filter. And also, in Ref. [8], in order to get a higher order cladding mode, the mode dispersion of cladding mode was tailored by etching the fiber cladding with a hydrofluoric acid. As decreasing the effective index of the cladding mode, they could enhance the spectral sensitivity to the index of liquid material. However, the process was cumbersome and, unfortunately, the spectral bandwidth was not wide enough. At last, in Ref. [9], an 84 nm bandwidth was achieved by a phase-shifted LPG made along an endless single mode photonic crystal fiber. However, the bandwidth of the stop-band, in which the pass-band was located, was only a little bit wider than that of the pass-band. The light beam having a wavelength out of the stop-band could not be blocked by the device, but continuously propagated along the core of the fiber. Accordingly, the operating bandwidth of the device was strongly limited.

In this paper, we present an ultra-wide band-pass filter based on the higher order cladding mode, which is excited by an LPG imprinted in the specially-designed single mode fiber. As the refractive index profile of the fiber has been properly designed, we can effectively enhance the mode coupling between the fundamental core mode and a high order cladding mode by an LPG. Further, the bandpass function has been achieved by using the evanescent field coupling between the cladding modes of two adjacent fibers [10-14]. In section 2, we qualitatively describe how to get the ultra-wide stop-band spectrum with an LPG written in a single mode fiber. In sections 3, the LPG-assisted evanescent field coupling between two attached fibers to get the pass-band is described in detail with experimental data. And then, the method used to adjust the spectral shape of the pass-band is followed in section 4. Finally, we show that the spectral shape of the ultra-wide pass-band can be switched from a flat-top style to a Gaussian one by applying strain to each LPG.

2. Wide stop-band induced by the mode coupling to a higher order cladding mode

An LPG makes mode coupling between the fundamental core mode and several cladding modes at specific resonant wavelengths, which correspond to a number of rejection or stop-
bands in its transmission spectrum. In general, the resonant wavelength of an LPG, $\lambda_{res}$ is determined by the well-known phase-matching condition [1],

$$\lambda_{res} = \Delta n_{eff} \Lambda,$$  \hspace{1cm} (1)

where $\Delta n_{eff}$ is the difference in the effective indices between the core mode and the involved cladding mode, and $\Lambda$ is the grating period. On the other hand, the spectral width of each stop-band for a strong coupling strength, is approximately given by [6]

$$\Delta \lambda \propto \Delta m \lambda^2,$$  \hspace{1cm} (2)

From Eq. (2), we can see that the bandwidth of the stop-band becomes wider for a shorter grating length $d$ or a longer resonant wavelength $\lambda_{res}$. Further, the bandwidth is inversely proportional to the difference between the effective group indices of the core mode and the involved cladding mode,

$$\Delta m = \Delta n_{eff} \frac{d \Delta n_{eff}}{d \lambda}. \hspace{1cm} (3)$$

It was reported that the differential group index, $\Delta m$, in conventional single mode fiber was decreased with the order of the involved cladding mode [15]. Therefore, according to Eq. (2), we can expect to get a wider bandwidth by utilizing a higher order cladding mode. Similarly, we can also obtain a wide bandwidth by using a short length grating. However, since the grating length is directly related with the grating strength, it is not easy to achieve a wide and deep resonant peak of an LPG by adjusting the grating length only. Further, a finer grating period is necessary to activate a higher order cladding mode, but it is also difficult to make a finer grating.

In order to enhance the efficiency of the mode coupling to the higher order cladding modes, we designed and fabricated a special germanium-doped single mode fiber (SMF) by using the modified chemical vapour deposition (MCVD) and fiber drawing processes. As shown in Fig. 1, the fabricated fiber had a cavernous refractive index profile and the average core index was low compared with that of a conventional SMF [16].

![Fig. 1. The refractive index profile of the fiber fabricated for the experiment. The average index of the fiber core is lower than that of a conventional single mode fiber.](image)

It is thought that the small index difference $\Delta \equiv 0.1 - 0.13\%$ of the fabricated fiber makes it easy the LPG-induced mode coupling to the higher order cladding mode by the reason presented with Fig. 2. In Fig. 2, we assumed that the refractive index profiles of two fibers are exactly the same to each other except the refractive indices of the cores; one has a high core index (a) and the other has a low index (b). In this case, the effective index of the core mode...
of the low index core fiber becomes lower than that of the high index core, but the cladding mode is not significantly affected by the minor change in the core owing to its large size compared with the core. Therefore, the LPG in the lower core index fiber induces the mode coupling to a higher order cladding mode. Furthermore, the low core index weakens the confining of the core mode and, thus, increases the efficiency of the mode coupling to a cladding mode. The mode coupling efficiency is proportional to the overlap integral between the two corresponding modes. Usually, the core mode of a conventional fiber is so small that its overlap with the cladding mode is not big enough to induce an effective coupling.

To generate the mode coupling from the fundamental core mode to a higher order cladding mode, a 20 mm-long LPG was imprinted in the specially-fabricated fiber. The fiber was hydrogen-loaded and illuminated with a 248 nm UV laser through an amplitude mask of a 400 μm grating period. The transmission spectrum of the proposed LPG was monitored during the UV inscription. Two resonant peaks were observed at two separated wavelengths and then they were merged into one peak as the UV-dose increased. As a result, we could get a wide and deep stop-band as shown in Fig. 3(a).

According to Fig. 3(a), it seems that the TAP (turn around point [6]) of the LPG spectrum happened between the red and blue lines in a time sequence. Thus, we can say that the red one was slightly under coupled but the blue one was over coupled a little bit. The remarkable point is that the mode coupling stronger than 20 dB (more than 99% mode conversion efficiency) happened over a spectral range as wide as 100 nm. To verify which mode is activated, the near field intensity pattern of the activated mode was taken by using an infrared camera and a tunable laser source. It shows that the activated mode is the LP 08 cladding mode.
3(b) was obtained. It had 7 rings around a central peak, which means the LP\textsubscript{08} cladding mode was activated.

### 3. Wide pass-band achieved with the evanescent field coupling between two fibers

Even though the LPG written in the specially-designed low index core single mode fiber had a wide bandwidth, it was a stop-band, not a pass-band. The bandpass function of the proposed filter was achieved by employing the evanescent field coupling phenomenon happened between two fibers. By placing two fibers side by side, each fiber includes an LPG, the mode coupling between the cladding modes of both fibers was invoked as shown in Fig.4. In order to aid the evanescent field coupling, the fibers were slightly twisted over each other, which method secured stable contact between the fibers. The LPGs in both fibers were designed to be identical and separated by an offset distance $L$ along the length.

In this configuration, the coupling between the core and cladding mode was occurred by the ultra-wide band LPG described in the previous section and then the coupling between two fibers was occurred through the evanescent fields of cladding modes.

![Fig. 4. Schematic of the proposed LPG-assisted band-pass filter. The core mode beam of a fiber is coupled to one of its cladding modes by an LPG (top fiber). Through the evanescent field coupling, the cladding mode is coupled to the cladding mode of the other fiber (bottom fiber). Finally, the output coupling is made to the core mode by the second LPG separated by $L$.](image)

The spectrum of the output beam through the drop-port of Fig. 4 was measured with respect to the offset distance $L$, the distance between the centers of both LPGs. As can be seen in Fig. 5(a), the output spectrum formed a pass-band and the output intensity increased with the offset distance. The most interesting thing was that the spectrum was rather flat over a very wide spectral range for most offset distances. The detail spectrum, for the case of an 80 mm offset distance, is depicted in Fig. 5(b). The 3 dB bandwidth was as wide as 160 nm, and the minimum insertion loss was $\sim 2$ dB including splicing losses. The effective bandwidth of $\sim 160$ nm is the largest one reported up to now, to the best of our knowledge. The black line in Fig. 5(a) is the ideal spectrum calculated from the transmission spectra of both LPGs used for experiments.

To obtain the coupling efficiency of the proposed device, the minimum insertion losses were measured for various offset distances and depicted in Fig. 6. The measurement was done at a wavelength of 1510 nm. From the figure, the efficiency was found to increase with the offset distance in the beginning and then decreased smoothly. It is in a sinusoidal pattern, which is very general for the case of mode coupling between two co-propagating modes. The similar behavior was experimentally observed with the LPGs written in conventional fibers [17]. Experimentally, the minimum insertion loss of $\sim 2$ dB, including the splicing losses, was achieved at the offset distance of 80 mm as mentioned with Fig. 5(b). From the fitting curve shown with the red line in Fig. 6, we can expect a little more improvement with the optimal distance $L$ of around 95 mm. Because, theoretically, there is no critical mechanism that inhibits the mode coupling, we can expect further improvement in the coupling efficiency by inducing more secure contact between fibers.
In some applications, a wideband filter having a Gaussian-like spectral shape is preferred to the flat-top case. One of these can be found in the field of optical coherence tomography (OCT) [18]. The OCT gives a high resolution tomographic image of a biomedical sample without even touching the sample. Because OCT is based on a white light interferometer, the resolution of the system becomes better when the light source has a wider spectral bandwidth [19]. Moreover, the side-lobes in the interference fringes can be significantly depressed or disappeared when the spectrum has a Gaussian-like shape. In this section, we report that the Gaussian-like spectrum suitable for OCT applications can be achieved by inducing strain on one or both fibers composing the proposed device.

It is well known that the transmission spectrum of an LPG is affected by strain through the elongation of fiber as well as the photo-elastic effect [4]. Therefore, the transmission spectrum of the proposed ultra-wide bandpass filter can be tailored to some extent by applying strain on one or both of the LPGs. At first, the transmission spectrum of an LPG was measured for various strains ranging from 0 up to 5385 με. As shown with Fig. 7, the initial spectrum (the black line) taken at zero-strain had two resonant peaks well separated by more than 100 nm. As strain was increased, the peaks moved toward each other and combined into one (the red line). With further strain, the depth of the resonant peak became shallow, but the resonant wavelength was not appreciably changed. The strain sensitivity can be regarded as a linear relationship at the specific wavelength range, but the sensitivity is saturated near the
wavelength where the TAP happens. According to the measurements shown in Fig. 7, we can see that the LPG written in the specially-designed low index core fiber has two resonant peaks of the same mode order, and both peaks moves to each other with a strain sensitivity of ~ 0.01 nm/με, in average.

![Fig. 7. The evolution of the transmission spectrum of an LPG under strain.](image)

This strain-induced evolution of the spectrum was very similar with the one observed during the LPG inscribing process. Fig. 3(a) showed two instances of the UV dose-induced evolution. However, the adjustment of strain is much easier than the control of the UV dose because the strain is reversible while the UV dose is not. For the wide band-pass filter as shown in Fig. 5, we have used the LPGs, having two separated resonant peaks, represented with the black line in Fig. 7.

To adjust the pass-band spectrum, we independently applied strain to each LPG. In detail, a longitudinal strain was applied along the fiber including the fiber twisting region as well as the LPG. Therefore, the physical contact between two fibers could be easily altered by the strain. A more secure apparatus, which can give strain without affecting the physical contact, is expected to reduce the insertion loss of the proposed device. Figure 8 shows one of the results obtained with the proposed scheme. The overall spectral shape was smooth and the full width at half maximum (FWHM) was as wide as ~ 120 nm. Unfortunately, the insertion loss was increased up to ~ 4.18 dB. The increment of the loss might be resulted from the loosening of the physical contact between two fibers as mentioned.

![Fig. 8. Transmission spectrum of the proposed bandpass filter. By controlling the strain on fibers, the spectral shape could be tailored into a Gaussian-like one.](image)

In this work, we have presented a wide bandpass filter based on the evanescent field coupling between LP_{08} higher order cladding modes activated by the LPG. Of course, other
cladding modes such as LP_{07} and LP_{09} modes can be also considered in this work, but their resonant wavelengths are not suitable and also of no interest for real applications. In particular, since the dual peak formation of an LPG is strongly related to the dispersion of the differential effective index, the spectrum having dual peaks centered at a specific wavelength can not be achieved only with the grating period adjustment. Therefore, the dispersion properties of the core and cladding modes of the fiber under test must be cooperative [7, 8]. In our experiment, with a grating period of 400 µm, fortunately, we could have dual peaks of the LP_{08} cladding mode centered at the 1.5 µm communication band. By controlling the grating period, we might be able to activate the nearby LP_{07} or LP_{09} cladding modes. However, the dual peak formation and/or the low insertion loss might not be guaranteed, in general.

5. Conclusions

We have demonstrated the optical fiber-based spectral shaping filter that had a ~ 160 nm ultra-wide pass-band and a 2 dB minimum insertion loss. To get the broad bandwidth, a special single mode fiber, characterized by the low index core, was designed and fabricated. Owing to the low index of the core, the LP_{08} high order cladding mode could be easily activated by an LPG having a moderate grating period of 400 µm. The dispersion properties of the effective index of a high order cladding mode allowed getting a wide stop-band in the transmission spectrum of the LPG. To get the bandpass property, the evanescent field coupling method was utilized. The cladding mode of a fiber, coupled by an LPG, was led to have the mode coupling with the cladding mode of another fiber. Two fibers were directly attached side by side and then slightly twisted over each other to secure physical contact between them. The separation between the LPGs was controlled to get the proper coupling ratio. Finally, the cladding mode in the second fiber was coupled back to its core mode by the second LPG. Because only the light component coupled by the LPG in the first fiber could be coupled to the second fiber, the bandpass property could be achieved.

In experiment, two types of wide bandpass filters were fabricated; the first one had a flat-top spectrum and the other had a Gaussian-like spectral shape. For the flat-top case, we achieved a 3 dB bandwidth including the insertion loss as wide as 160 nm; the widest one to the best knowledge of authors. The maximum mode coupling of ~ 2 dB insertion loss was obtained at a separation length of about 80 mm. By applying axial strain on the fibers, the transmission spectrum of the filter could be tailored to some extent. The dual peaks of the LPG, separated by more than 100 nm, could be merged into one peak by applying a strain of 4600 με. Using these properties, the flat-top spectrum of the proposed filter could be switched to the Gaussian-like one having a ~ 120 nm FWHM and a minimum insertion loss of 4.18 dB, which is suitable for optical coherence tomography applications. Although the insertion loss was a little bit large yet, by devising an apparatus that can apply strain on the LPGs while securing the physical contact between fibers, the proposed ultra-wide bandpass filter can have a strong potential as a practical device.

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