Band-selection filters with concatenated long-period gratings in few-mode fibers

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We demonstrate a novel device that comprises a pair of broadband and narrowband long-period gratings written in specially designed few-mode fibers to achieve in-fiber bandpass filtering. This device configuration opens the possibility of using long-period gratings for complex spectral shaping in a band-selection as opposed to the conventional band-rejection configuration. The devices are low loss (<0.5 dB) as well as tunable over large spectral ranges (26 nm). We demonstrate, for the first time to our knowledge, that the unique dispersive properties of long-period gratings allow for constructing dispersion-free bandpass filters with arbitrarily sharp spectral profiles. © 2002 Optical Society of America

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Investigations of long-period fiber gratings (LPGs) have focused primarily on the gratings' band-rejection properties.[1] The applications for LPGs considered thus far have required relatively broad spectral features. Thus, whereas dispersive characteristics of the modes in a fiber have been studied for shaping LPG spectra,[2,3] dispersion that arises from the LPG filter itself has not been addressed.

We report a novel device configuration that comprises a pair of broadband and narrowband LPGs in specially designed few-mode fibers, which serves as a platform for building band-selection (as opposed to band-rejection) filters. We show that such filters are dispersion free, even though a LPG with identical bandwidth (3 dB, $\Delta\lambda \sim 2.5$ nm) operated in the conventional configuration as a band-rejection device can add significant dispersion (>10 ps/nm). The loss of the band-selection filters is less than 0.5 dB, and the filter can be tuned over a wavelength range of 26 nm. This configuration allows for complex spectral shaping by tailoring the spectral characteristics of only one of the pair of LPGs.

In this report we consider the dispersive effects of LPG-based filters and demonstrate a novel device configuration that is dispersion free. Potential applications include bandpass filters that serve as frequency selectors for fiber-laser cavities and filters for all-optical regenerators.[4] In these regimes, filters with sharp spectral features would be required, and thus the dispersive characteristics of LPG filters must be addressed. In particular, filters for all-optical regenerators with dispersion values $>\pm 10$ ps/nm can lead to pulse distortions.[4] A previously reported technique[5] for fabricating bandpass filters by use of two conventional LPGs employs a discrete core block, i.e., a loss element to selectively attenuate the core mode. That device was inherently lossy (loss of >2 dB) because of the core block, and tuning such a filter would require precise simultaneous tuning of two identical LPGs. In addition, the gratings in such a filter coupled light into a higher-order cladding mode, which is susceptible to loss as well as to environmental and mechanical instabilities.

The bandpass filter demonstrated here utilizes the unique mode-conversion properties of LPGs in few-mode fibers. The spectral characteristics of a LPG are determined by its phase-matching relationship, which relates the resonant wavelength of coupling to the grating period. Figure 1 shows that a few-mode fiber can be designed to have a turn-around point (TAP) in its phase-matching relationship (i.e., the phase-matching curve is not monotonic, as is the case for conventional LPGs). The TAP occurs at a wavelength at which the group velocities of the two coupling modes are identical.[2] If the two modes have identical group velocities, the phase-matching condition is preserved over a large wavelength range; such a LPG couples over a relatively broad wavelength range.[6] This effect was used[2] to demonstrate mode converters with greater than 99% mode conversion over bandwidths of ~63 nm. If this few-mode fiber is dimensionally scaled, the phase-matching relationship shifts such that the TAP now occurs at a different wavelength and grating period.

One can achieve such dimensional scaling by drawing the same few-mode fiber to various outer diameters (ODs). This is illustrated in Fig. 1, which shows the phase-matching relationship for fibers drawn to the ODs that range from 110 to 121 μm. Figure 1 shows that, whereas the fiber with an OD of 121 μm has a TAP at 1550 nm, fibers of other ODs

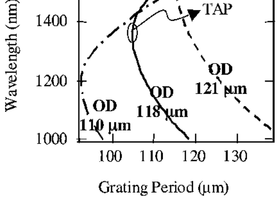

Fig. 1. LPG phase-matching curve in dispersion-tailored few-mode fibers exhibits a TAP. LPGs written at the TAP yields large mode-conversion bandwidths. The TAP can be shifted by dimensional scaling of the fiber.

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yield a phase-matching curve that varies monotonically at 1550 nm. Thus a LPG written in the fiber with an OD of 121 μm will yield a broadband spectrum at 1550 nm, whereas a LPG written in fibers with other ODs will yield a conventional, narrowband spectrum.

A schematic of our device is shown in Fig. 2(a), which illustrates that LPGs in few-mode fibers drawn to two different ODs (denoted I and II) are spliced together to compose a bandpass filter. The spectra obtained by writing LPG in these two fibers are shown in Fig. 2(b). The phase-matching curve for fiber I (OD of 121 μm) has a TAP at 1540 nm, and a LPG written at the corresponding grating period ($\Lambda = 112.5\ \mu$m) converts the incoming LP_{01} mode into an LP_{02} mode over the entire C band. This grating has a length of 1 cm and an UV-induced index modulation of $\Delta n \sim 5 \times 10^{-4}$. Fiber II is a similar few-mode fiber but is drawn to an OD of 112 μm. In the 1550-nm spectral range the phase-matching curve for this fiber exhibits a monotonic variation. Figure 2(b) shows the spectrum of a 10-cm long uniform LPG written in Fiber II. A LPG with a period of 120 μm and a UV-induced index modulation of $\Delta n \sim 2 \times 10^{-4}$ yields a narrowband resonance that is 14 dB strong.

The device functions as follows: All light in an entire communications band passing through LPG I is converted to the LP_{02} mode. Splicing the two fibers converts the LP_{02} mode of fiber I adiabatically into the LP_{02} mode of fiber II. Then the LPG II selects a specific narrow portion of the spectrum back into the LP_{01} mode. This results in a bandpass filter, as shown in Fig. 2(c). The 3-dB bandwidth of this filter is ~2.5 nm, and the peak isolation is -10 dB.

The device illustrated in Fig. 2 provides a general platform for building band-selection as opposed to band-rejection filters with LPGs. The first mode converter (LPG I) serves only as a device that provides a spatially modified input for LPG II and does not define the spectral characteristics of the bandpass filter. The spectrum of the filter is uniquely defined by the inverted spectrum of LPG II alone, facilitating spectral shaping in the band-pass configuration by varying the spectral properties of LPG II. This concept is illustrated in Fig. 3, which shows the conventional band-rejection spectra of three distinct LPGs and the corresponding bandpass spectra when these LPGs were used as LPG II for the bandpass filter. Fiber I and LPG I were the same as those used for the experiments illustrated in Fig. 2: All experimental spectra described in this Letter utilize the same input conditions (and thus the same LPG I). Figure 3 shows that the conventional spectral shaping tools used with LPGs as loss filters, such as control of the grating length (therefore bandwidth) and strength, can also be used in the band-selection configuration.

To investigate the tunability and loss characteristics of these devices, we assembled a bandpass filter in which the OD of fiber II is 118 μm. The 3-dB bandwidth of the 57-mm long narrowband LPG (LPG II) is 6.5 nm. Figure 4 shows the effect of temperature tuning of the resonance. Increasing the temperature over a range of 180 °C monotonically moves the bandpass resonance from 1538 to 1564 nm. The isolation for this filter is ~10 dB and is limited by the sidebands of LPG II; apodizing the grating should permit 35-dB isolation to be achieved. The excess loss for the LP_{02} mode was measured to be 0.4 dB. Because the fundamental mode of this fiber and that of standard transmission fiber are closely mode matched, we estimate that the loss of a fully pigtailed device will be less than 0.5 dB. Because the bandpass filter does not employ any extraneous attenuators, the insertion loss of this device is significantly less than what was previously reported when core blocks were used. Also, note that the tunability of this filter is uniquely facilitated by the device configuration employed, because only one LPG needs to be tuned.

Consider a fiber that is guiding two modes with electric field amplitudes E_1 and E_2, which are coupled by a LPG. If all light in the fiber resides in mode 1 before

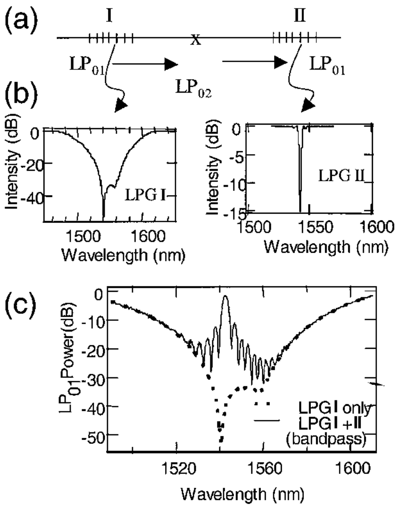

Fig. 2. (a) Schematic of a bandpass filter. The splice ensures adiabatic transition of the LP_{02} mode from fiber I to fiber II. Arrows show dominant modes of propagation. (b) LP_{01} transmission spectra of LPG I and II: LPG I, broadband TAP resonance; LPG II, conventional narrowband resonance. (c) Resultant bandpass spectrum: spectrum defined by the characteristics of LPG II alone.

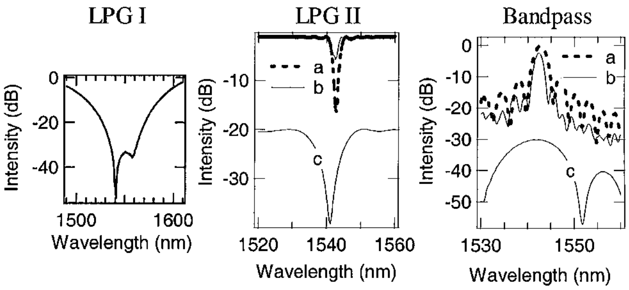

Fig. 3. Spectral shaping in a bandpass configuration. The bandpass spectrum is controlled by the spectrum of LPG II only. Three kinds of LPG II are shown: (a) 14 dB strong; 3-dB $\Delta\lambda$ ~2.5 nm; fiber II OD, ~112 μm; (b) 5 dB strong; all other parameters the same as in (a); (c) 13 dB strong; 3-dB $\Delta\lambda \sim 7$ nm; fiber II OD, ~118 μm.

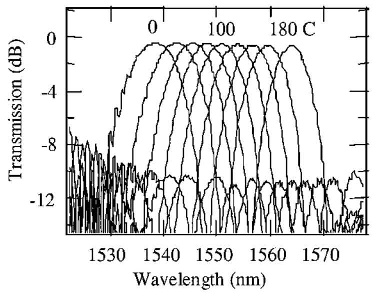

Fig. 4. Tunability and loss characteristics of a bandpass LPG. Tuning requires tuning of LPG II only. Thermal tuning of filter, 26-nm range with 180 °C temperature change. Filter insertion loss, ~0.4 dB.

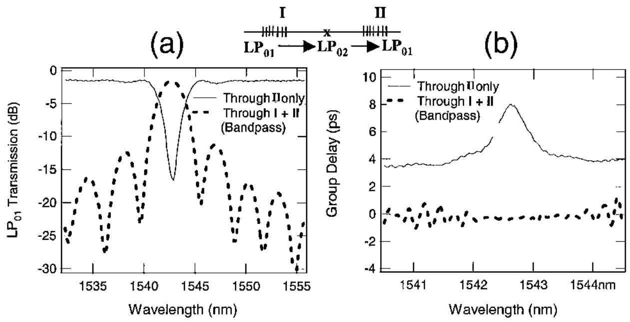

Fig. 5. (a) Transmission and (b) GD response for conventional and bandpass filters. Conventional filters, solid curves; bandpass filters, dashed curves. The 3-dB $\Delta\lambda$ (2.5 nm) is the same for both filters. Conventional filters, $D \sim \pm 10$ ps/nm. The bandpass filter is dispersion free. GD ripple, <1 ps within the 3-dB bandwidth.

it encounters the LPG, the input condition is given by $E_1 = 1$ and $E_2 = 0$, and the complex amplitudes at the output of the LPG are given by[7]

$$E_1 = \left[\cos^2(L\sqrt{\kappa^2 + \delta^2}) + \frac{\delta^2}{\kappa^2 + \delta^2}\sin^2(L\sqrt{\kappa^2 + \delta^2})\right]^{1/2} \times \exp\left\{i\tan^{-1}\left[\frac{\delta}{\sqrt{\kappa^2 + \delta^2}}\tan(L\sqrt{\kappa^2 + \delta^2})\right]\right\},$$

$$E_2 = \left[\frac{\kappa}{\sqrt{\kappa^2 + \delta^2}}\sin(L\sqrt{\kappa^2 + \delta^2})\right]\exp(i\pi), \qquad (1)$$

where κ is the coupling efficient, L is the length of the LPG, and δ is a detuning parameter that is a function of wavelength.[7] It reveals that, whereas the phase response of E_2 is not a function of wavelength (the phase has a constant value of π), the phase response of E_1 is strongly coupled with its magnitude response. As a LPG becomes spectrally sharp, the magnitude of E_1 varies rapidly with wavelength; likewise, the phase response also shows strong wavelength dependence. Thus a signal that passes through a sharp LPG-based band-rejection filter will accumulate significant dispersion. The scattered mode, E_2, has no spectral phase variation and will always be dispersion free.

Because the bandpass filters discussed in this Letter transmit only the cross arm (E_2) from LPG II, they are expected to be inherently dispersion free. To test this concept we fabricated narrowband LPG in fiber II drawn to an OD of 112 μm. A 100-mm long LPG in this fiber yielded a resonance at 1542.6 nm with a 3-dB bandwidth of 2.5 nm. Figure 5(a) shows the spectra of the gratings in the conventional notch–filter and bandpass configurations, respectively. Figure 5(b) shows their corresponding group-delay (GD) responses measured with the modulation phase-shift technique. For the notch filter the GD rose sharply with wavelength, resulting in dispersion values as high as ±10 ps/nm close to resonance. When the same grating was deployed in the bandpass configuration, the GD remained constant throughout the resonance, implying that these bandpass filters are dispersion free. It must be noted that the dispersion-free nature of the bandpass filters will be maintained as long as LPG II is not intentionally chirped and as long as the apodization profile is symmetric.

Figure 5(b) indicates that, whereas the GD of the bandpass filter remained spectrally flat, there was some GD ripple (~1 ps). The ripple was negligible at the resonant wavelength of the filter but increased thereafter. The amount of ripple is caused by intermodal interference between light in the desired mode (whose path is LP_{01}–LP_{02}–LP_{01}) and any unfiltered LP_{01} light that passes through the device. This impairment is not inherent in this device configuration and can be mitigated by fabrication of stronger broadband mode converters (LPG I) and by ensuring adiabatic splice transitions.

We have demonstrated a dispersion-free, spectrally sharp ($\Delta\lambda \sim 2.5$ nm) bandpass filter with long-period fiber gratings in specially designed few-mode fibers. These filters are based on a novel platform of a pair of broadband and narrowband mode converters that offer the flexibility of complex spectral shaping as well as tuning (26 nm) while they achieve the lowest loss (<0.5 dB) of any bandpass filtering device. The device works in transmission and requires no additional components such as circulators.

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