Wavelength-division multiplexing isolation filter using concatenated chirped long period gratings

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Abstract

We propose the use of concatenated chirped long period gratings as an efficient wavelength-division multiplexing (WDM) isolation filter. The proposed filter not only works in the transmission mode but also has almost equispaced pass bands with high isolation at the stop bands. The filter has negligible dispersion effects in the pass band, which should make such a device suitable for use in WDM fiber optic communication links.

Keywords: Fiber gratings; Chirped long period gratings; Wavelength-division multiplexing; Isolation filters

1. Introduction

Wavelength-division multiplexing (WDM) has now become highly important for increasing the transmission capacity of optical fiber systems. In a WDM based system, high isolation loss between adjacent channels is required so that there is less interference from source instability and less cross talk between neighboring channels. There has been extensive research in recent years to develop isolation filters capable of separating out large number of channels with least signal degradation. In general a transmission based filter is advantageous over a reflection based filter which would require optical circulators. Along with the desired amplitude response, phase response of filters in WDM based system has also become an important consideration [1]. Some of the reflection based isolation filters proposed are compound phase shifted Bragg gratings, multiple short period gratings and superstructure gratings [2,3]. Most of these require multiple units to yield multiple isolation peaks, which increases insertion loss. Also dispersion effects of these are considerable [1]. Since each of these channels may pass through multiple units while being reflected out, there may be signal degradation due to out of band dispersion of the fiber gratings which may limit transmission distance.

Long period gratings, which enable coupling between co-propagating modes, have been of considerable research interest in recent years [4]. Most of these were based on their applications in flattening the gain spectra of EDFA [5]. Recently application of uniform LPG in devising transmission based dispersion compensators was proposed [6]. Although chirped Bragg gratings have been an
area of extensive research mainly in dispersion compensation applications \[7\], the potentials of chirped long period gratings have not been exploited completely. Some efforts to understand the transmission characteristics of chirped long period gratings have been made \[8\] and their use in dispersion compensation was proposed \[9\].

Recently, WDM isolation filters using concatenated uniform long period gratings have been demonstrated in Ref. \[10\], where they could obtain isolation peaks within the profile of a single LPG loss peak and the isolation loss of the filter varied according to the single grating transmission profile. This limits the wavelength range in which high isolation peaks could be obtained. In this paper we propose the use of a pair of concatenated chirped long period gratings, as efficient WDM isolation filters. The proposed device is shown to exhibit almost uniformly spaced pass bands. The device has high isolation and the bandwidth of the pass band/stop band is also adjustable. Dispersion in the pass band is shown to be negligible, which is a highly desirable characteristic for isolation filters. The design proposed here overcomes the limitation of the filters based on uniform LPGs and provides an extra degree of freedom obtained by chirping the long period gratings.

The remainder of the paper is organized as follows. In Section 2 effects of chirping a long period grating is briefly discussed. Section 3 gives the proposed design of WDM isolation filter using two concatenated chirped long period gratings and discusses the obtained results. Concluding remarks are given in Section 4.

2. Effect of chirp on the transmission characteristics of long period gratings

The coupled mode equations describing the mode coupling in long period gratings are given by \[4\]

\[
\begin{align*}
\frac{dE_1}{dz} &= -i\kappa E_2 - i\delta E_1 \\
\frac{dE_2}{dz} &= -i\kappa E_1 + i\delta E_2
\end{align*}
\]

where \(E_1\) and \(E_2\) are the electric field amplitudes of the core and cladding mode respectively, \(\kappa\) is the coupling coefficient denoting the strength of coupling between the two modes and \(\delta\) is the detuning parameter given by \(2\delta = \beta_{\omega} - \beta_{\lambda} - 2\pi/\Lambda\). \(\beta_{\omega}\) and \(\beta_{\lambda}\) are the propagation constants of the core mode and the cladding mode respectively and \(\Lambda\) is the grating period.

For chirped gratings where the grating period and hence the coupling coefficient and detuning varies along the grating length, closed form solutions of Eq. (1) cannot in general, be obtained, thus necessitating the use of numerical techniques. In chirped gratings the grating period \(\Lambda\) depends on \(z\). Thus in the case of linearly chirped gratings the grating period varies linearly over the grating length as

\[
\Lambda(z) = A_0 + C(z - L_{\lambda}/2) \quad \text{negatively chirped}
\]

\[
\Lambda(z) = A_0 - C(z - L_{\lambda}/2) \quad \text{positively chirped}
\]

where \(L_{\lambda}\) is the grating length, \(A_0\) is the grating period at \(z = L_{\lambda}/2\) and \(C\) denotes the grating chirp. Positive chirp represents decreasing grating period with distance while negative chirp represents increasing grating period. For uniform index modulation, chirping the grating affects only the detuning parameter along the grating length. The detuning for a given wavelength now varies along the grating length and is given by

\[
2\delta(z) = \beta_{\omega} - \beta_{\lambda} - \Omega(z) \quad \text{where} \quad \Omega(z) = 2\pi/\Lambda(z)
\]

Throughout our analysis chirp is controlled to enable coupling to only one cladding mode. To analyze chirped long period gratings we have used the well-known transfer matrix method \[11\].

It is known that chirping the grating results in decrease in the peak coupling and broadens the spectrum. The spectral broadening will depend on the range of wavelength which experiences coupling across the grating length. Thus as the chirp increases the transmission spectrum broadens. If the detuning is chosen to be symmetric about the central wavelength, then the response will also be symmetric. The extent of spectral broadening for a given chirp would also depend on the order of the cladding mode into which coupling occurs \[8\]. Fig. 1 shows the variation of resonance wavelength with change in grating period for different cladding
modes in a fiber with $A = 0.005$, core radius $= 2.5 \mu m$ and cladding radius $= 62.5 \mu m$; these parameters are the same as in Ref. [4]. It can be seen that slope of the variation decreases with increasing cladding mode order i.e., when $\beta_{co} - \beta_{cl}$ increases. This shows that the range of periodicity (chirp) required to attain a specific wavelength range of broadening would be larger for coupling to lower order cladding modes.

Fig. 2 shows the effect of chirp on the transmission spectrum of an LPG of length 40 cm, peak refractive index modulation of $0.5 \times 10^{-4}$ in a fiber with parameters chosen as for Fig. 1, where we consider coupling to $LP_{01}$ cladding mode. It can be seen that the chirping broadens the spectrum with a corresponding reduction in the transmission loss. This is because the effective length over which the coupling occurs for each wavelength has now considerably reduced but coupling in a larger range of wavelength is enabled by chirping the grating. Thus by suitably choosing the length and grating chirp, desired spectral response can be obtained. This could prove useful in flattening the gain spectra of EDFA and for matching to any arbitrary required profile.

3. WDM isolation filter using concatenated chirped LPGs

Consider two chirped long period gratings concatenated symmetrically as shown in Fig. 3. The two concatenated chirped LPGs will act as a Mach-Zender interferometer for the range of wavelengths for which coupling is enabled by the chirped gratings. The first grating couples part of the core mode intensity in to the cladding mode and the second grating recombines them. Due to the phase difference accumulated by the core mode and the cladding mode brought about by propagation through the core and the cladding respectively, at the second grating, the interference is constructive or destructive depending on the wavelength, leading to a periodic transmission spectrum. By varying the chirp or the total device length, the periodicity of the interference pattern can be changed.

The main design consideration in such a filter is to select the chirp and the refractive index modulation of the first grating such that approximately 50% of the power is coupled to the cladding mode over the desired wavelength range. The second grating has then to be symmetrically concatenated.
to the first one to get equispaced interference maxima. The regions of maximum transmission act as pass bands and those of minimum transmission act as stop bands. The spectral width of the loss peaks can be reduced by increasing the grating length or choosing to couple to a higher order cladding mode, while chirping the grating enables control of the wavelength range for which the fringe pattern is desired.

Fig. 4 shows the core mode transmission in the EDFA band at the end of the second grating when two LPGs of length 40 cm each are concatenated. The gratings have a peak index modulation of $0.5 \times 10^{-4}$ and fiber parameters are the same as in Fig. 1. Here the gratings were chirped with a chirp $C = 8.5 \times 10^{-5}$ and $A_0 = 599 \text{ nm}$. These parameters ensure coupling to only the LP$_{11}$ cladding mode. There are about 32 pass bands with an average wavelength spacing of 1.175 nm. The variation in wavelength spacing in the range 1530–1560 nm is less than 2%. The 3 dB width of the pass bands is about 0.6 nm and there is high isolation at the stop bands (above 15 dB). Interference peaks over a wider range could also be obtained by increasing the chirp parameter within the limits to ensure prominent coupling to a single cladding mode. The width of the pass bands can be changed by changing the device length or by choosing to couple to a different cladding mode.

It is important for the isolation filters to have negligible dispersion effects in the pass band. The delay difference acquired due to the group velocity difference between the core mode and cladding mode could cause dispersion effects. This principle has indeed been proposed for dispersion compensation [9]. But in our case since coupling to very low order cladding modes are considered, the delay difference achieved by travelling the considered grating length is very small, resulting in negligible dispersion. Fig. 5(a) shows a single pass band from Fig. 4 and Fig. 5(b) shows the corresponding dispersion response. The delay response and the dis-

Fig. 4. Transmission characteristics of two concatenated chirped LPGs of 40 cm each with $C = 8.5 \times 10^{-5}$.

Fig. 5. (a) One pass band from the interference pattern shown in Fig. 4; (b) dispersion response corresponding to the pass band shown in (a).
persion has been calculated by finding the phase \( \phi \) from the complex transmission amplitude of the core mode at the end of the second grating. Fig. 5(b) shows the plot of \( d^2 \phi / d\omega^2 \) in ps\(^2\) which is seen to be negligible as expected due to the coupling to very lower order cladding mode being considered.

The obtained results show that chirped long period gratings could be used as efficient WDM isolation filters. The flatness of the pass band could be improved by varying the fiber or the grating parameters. More work in this direction is under way. The sensitivity of the LPG transmission spectrum to fiber parameters and the refractive index of the external medium could be tailored to fabricated a tunable WDM isolation filter. A few solutions to decrease the sensitivity of the LPG based devices have been proposed [9,12]. The bend sensitivity of the device that is proposed here would be less due to the considered coupling to a lower order cladding modes. Thus with proper packaging the proposed device working in transmission mode could be useful in communication links.

4. Conclusion

In conclusion, we have discussed the effect of chirp on LPG transmission characteristics and proposed an efficient WDM isolation filter using a pair of symmetrically concatenated chirped long period gratings. The proposed device is shown to have almost equispaced pass bands with high isolation at the stop bands. The filter characteristics can be varied by adjusting the grating parameters and length. These filters working in transmission mode also show negligible dispersion in the pass band making them suitable for use in optical communication links.

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References