Optical add/drop multiplexer using short- and chirped long-period fibre gratings for dense wavelength-division multiplexing

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Abstract—We propose and demonstrate the use of a novel wavelength-tuneable optical add/drop multiplexer (OADM) device based on fibre Bragg gratings (FBGs) and chirped long-period gratings (CLPGs) having a broad transmission spectrum. Numerical simulations predict bandwidths in the range of 40 nm and higher. Fabrication of the symmetric CLPGs, and the method of strain used for tuning of the fibre Bragg grating are also discussed.

Index Terms—Wavelength-tuneable, Add/drop multiplexer, Fibre Bragg gratings, Chirped long-period gratings.

I. INTRODUCTION

Dense wavelength-division multiplexed (DWDM) networks require low insertion loss (< 0.5 dB), high channel isolation (> 30 dB), low back-reflection, wide-range wavelength selectivity, low cross-talk (< −39 dB), and economically viable optical add/drop multiplexers. This paper proposes the design of a novel broadband add/drop multiplexing device, that consists of short- and chirped longperiod fibre gratings.

Due to low back-reflection, low insertion loss, ease of fabrication, and high channel isolation of LPGs [13], transmission grating technology finds application in dispersion compensation, and in band rejection filters [19]–[21]. These types of fibre gratings also find applications in sensing [1], [11], add/drop multiplexing applications [9], [24], and gain equalization of erbium-doped fibre amplifiers (EDFAs) [18], [22].

Long-period gratings are periodic perturbations in an optical fibre that enable the coupling of power between two co-propagating modes. Fibre Bragg gratings involve the coupling of a forward propagating guided mode to an identical counter-propagating mode. Recently, there has been an interest in transmission gratings that produce high isolation broadband transmission spectra (bandwidths > 50 nm). It has been shown that bandwidths in the range of ~ 60 nm → 100 nm can be achieved [12], [15]. This transmission grating property will increase the flexibility of a DWDM network, by coupling of a wide range of wavelengths at once.

In this paper, we propose a means for creating a broadband add/drop multiplexing device that drops several International Telecommunication Union (ITU) DWDM channel signals in a selected wavelength range with a suitable channel spacing, from one single-mode optical fibre to the next using identical chirped transmission gratings. A short-period grating, which is tuned in a third optical fibre, and an optical circulator are then used to drop a specific wavelength channel. This dropped channel can later be added to the remaining DWDM channels.

The remainder of the paper is organized as follows. In Section II fibre grating theory is briefly discussed, and Section III gives the proposed design of the OADM. Concluding remarks are given in Section IV.

II. BACKGROUND

The refractive-index modulation of a fibre grating along the length of a fibre can be written as [2]:

\[
u(z) = \nu_{\text{core}} + \Delta n_{\text{eff}} \left( \cos \left( \frac{2\pi}{\Lambda} z + \phi(z) \right) \right)
\]

(1)

where \(\nu_{\text{core}}\) is the effective refractive-index of the fundamental \(LP_{01}\) core mode, \(\nu\) is the fringe visibility, \(\Lambda\) is the grating period, \(\Delta n_{\text{eff}}\) is the induced index change spatially averaged over the fibre grating period, and \(\phi(z)\) denotes the grating chirp.

A. Fibre Bragg gratings

Since the dominant interaction in a bragg grating is the reflection of a particular mode of amplitude \(A(z)\) into a similar counter-propagating mode of amplitude \(B(z)\), the simplified coupled-mode equations for FBGs then look as follows [7]:

\[
\frac{dA}{dz} = i\sigma A(z) + i\kappa B(z)
\]

\[
\frac{dB}{dz} = -i\sigma B(z) - i\kappa^* A(z)
\]

(2)

where \(A(z)\) is the forward mode, \(B(z)\) is the reverse mode, \(\kappa\) is defined as the “AC” coupling coefficient, and \(\sigma\) is the general “DC” self-coupling coefficient. The two modes, \(A(z)\) and \(B(z)\), represent slowly varying mode envelope functions [8].

The spectral dependence and diffraction efficiency of fibre
gratings can be obtained by using the coupled-mode theory, since it accurately models the optical properties of most fibre gratings.

B. Long-period gratings

The coupled-mode equations describing the mode coupling in transmission gratings are defined as follows [8]:

$$\frac{dA}{dz} = i\sigma A(z) + i\kappa B(z)$$
$$\frac{dB}{dz} = -i\sigma B(z) + i\kappa^* A(z)$$

(3)

The phase-matching condition for LPGs is defined as [8]:

$$\delta \equiv \frac{1}{2} \left( \beta_{\text{core}} - \beta_{\text{clad}}^n \right) - \frac{\pi}{\Lambda}$$

(4)

where $\delta$ is the detuning parameter, $\beta_{\text{core}}$ and $\beta_{\text{clad}}^n$ are the propagation constants for the $LP_{01}$ core mode and $n$th cladding mode respectively. $\lambda_r \equiv \left( n_{\text{core}} - n_{\text{clad}}^n \right) \lambda$ is the resonant wavelength for coupling to the $\mu$th ($LP_{\mu}$) cladding mode, where the azimuthal order of the mode is given by $\mu$.

Chirping the LPG period along the fibre axis causes the detuning parameter $\delta$ and coupling coefficient $\kappa$ to vary for different distances along the fibre axis. In our analysis of LPGs, coupling is done to a single cladding mode.

In the case of linearly chirped transmission gratings the grating period $\Lambda(z)$ can be expressed as [4]:

$$\Lambda(z) = \Lambda_0 \pm \xi \left( z - \frac{L_g}{2} \right)$$

(5)

where $L_g$ is the grating length, $\Lambda_0$ is the grating period at $z = L_g/2$, and $\xi$ defines the grating chirp. Increasing the grating period along the fibre length indicates negative chirp, whereas decreasing the grating period indicates positive chirp.

III. PROPOSED DESIGN AND COMPUTER SIMULATIONS

Fig. 1 illustrates the proposed design of a novel long-period grating add/drop multiplexer. Two chirped LPGs is placed in parallel in close contact ($< 5 \mu m$), to form a cladding-mode coupler without the need of fusion [24]. The chirped LPGs are fabricated such that the $LP_{01}$ core mode couples to the fifth cladding mode with a desired chirp. The cladding-mode propagates in the cladding and a coupling region between the two optical fibres, exciting a similar cladding mode in the parallel-placed fibre with an identically inscribed chirped LPG. The chirp should be chosen such that the desired bandwidth is obtained, allowing operation as a broadband device.

The tuneable Bragg grating and circulators perform the multiplexing/demultiplexing operation. The output of the circulator situated on the lefthand side of Fig. 1, can be multiplexed with the data dropped from the original fibre using appropriate methods.

A. Fabrication method for chirped long-period gratings

The exposure of germania-doped silica fibres to a KrF laser through an amplitude mask, producing a UV-induced index modulation in the fibre core, is the most common technique used to fabricate long-period fibre gratings [13]. This method does not produce azimuthally symmetric LPGs, and results in a high polarization-dependent loss of the particular grating.

$CO_2$ laser exposure of a fibre at 10.6 $\mu m$ has been demonstrated to produce LPGs with polarization insensitivity, and with high temperature stability [5]. When the fibre was annealed at $1200^\circ C$, it was also shown that the spectral properties of the LPG remained unchanged [6].

In this paper, we will consider fabrication of chirped LPGs in germania-doped silica fibre, using a pulse-width modulated $25 W CO_2$ laser to produce azimuthally symmetrically written fibre gratings, based on the point-by-point method [14].
alignment difficulty, and increase the focal spot size. The annular CO₂ laser beam is then deflected from a 45° tilted flat mirror parallel to the optical fibre. The deflected laser beam is focussed on the fibre core by a concave spherical mirror with diameter 37.8 mm and focal length of approximately 38 mm, for the symmetrical exposure of the fibre.

The flat and concave mirrors have been modified such that the fibre passes through it horizontally, and the fibre is supported by clamps. When the chirped LPG is fabricated using the point-by-point method, the translation stage moves in the axial direction to predetermined positions. The movement is in synchronization with the shutter in the carbon-dioxide laser beam.

B. Theoretical Results

The theoretical relationship between the long-period grating period Λ, and the coupled wavelengths is used to obtain the specified LPG resonant wavelength desired. Fig. 3 indicates the variation of resonant wavelength with grating period for the coupling to different cladding modes. The parameters used to simulate Fig. 3 are similar to those of Corning single-mode (SMF-28e) fibre, where Δ = 0.005, core radius a₁ = 4.1 µm, and cladding radius a₂ = 62.5 µm.

To obtain the characteristics of LPGs, it is required to plot these curves for a specific optical fibre, since the properties of the core/cladding refractive indexes and core/cladding sizes, differ from fibre to fibre. The slope of all the characteristic curves are positive as indicated in Fig. 3, but it can be predicted that for higher order cladding modes LPµ (µ > 9), the slopes of the curves approach infinity for wavelengths higher than 1600 nm.

By chirping the LPG, the transmission spectrum is broadened and will become wider for higher values of grating chirp ζ. The spectral broadening will not only depend on the different resonant wavelengths which experience coupling across the length of the fibre grating, but also on the order of the cladding mode into which coupling occurs [15], [19].

Fig. 4 illustrates the theoretically obtained transmission spectra of an LPG of 40 mm, induced index change Δn_{eff} = 0.83 × 10⁻³ for different values of chirp dλR/dz simulated for coupling to the fifth cladding mode. The fibre parameters are the same as those used in Fig. 3.

From Fig. 4 it can be seen that chirping of the grating period enables coupling over a larger range of wavelength. The transmission spectrum broadens as chirp in increased, and results in a lower value of transmission loss. If coupling was done to lower order cladding modes, the resulting transmission loss would be even lower. This could be very useful in the add/drop multiplexing device, or even in flattening the gain spectra of EDFA. Therefore, by adjusting the induced index change, length, and chirp, virtually any desired broadband spectrum can be obtained.

By tuning the fibre Bragg grating used in the proposed design illustrated in Fig. 1, a specific wavelength channel can be obtained. A low-cost piezoelectric ceramic fibre stretcher (PZT) is used for the tuning process by increasing the length of the FBG induced with an external voltage, and results in an increase of overall grating period along the fibre axis. The fibre Bragg grating is typically fabricated by using a germania-doped silica fibre exposed to a KrF excimer laser (Λ = 248 nm) through a phase mask [3]. The change in the resonant wavelength λr due to a change in strain Δε is given as [23]:

\[ Δλ_{strain} = λ_r (1 - ζ_e)Δε \]  

where ζ_e is the effective strain-optic constant given by [10]:

\[ ζ_e = \frac{n_c^2}{2} [ζ_{12} - ϱ(ζ_{11} + ζ_{12})] \]

ζ_{11} and ζ_{12} are the components of the strain-optic tensor, ϱ is Poisson’s ratio, and n_c is the effective index of the core. Typical values for a common silica single-mode optical fibre are: ζ_{11} = 0.153, ζ_{12} = 0.273, and ϱ = 0.17, where the wavelength-strain sensitivity at 1550 nm is approximately 1.2 pm/µε [1], [16].

The simulation results obtained for a 20 mm apodized FBG under varying external applied strain is illustrated in Fig. 5. The strain applied ranges from −1600 → 1600 micro strain
(µε), where the resonant wavelength λ₀ is 1550 nm with zero applied strain.

![Graph of resonant wavelength shift for a Kaiser-profile apodized FBG under varying external strain.](image)

By applying positive strain (increasing voltage on the piezoelectric ceramic fibre stretcher), the grating period Δ increases, and the central wavelength is shifted to higher values. This is vice-versa when negative strain is applied. The relationship between the strain applied and the varying resonant wavelength λ₀ is constant. The wavelength stability is affected significantly, since Bragg gratings are quite sensitive to thermal fluctuations [17]. It has been shown that the wavelength and applied strain sensitivity to the voltage applied is approximately 1 nm/V, and 85.4 µε/V respectively, when coupling is done to the LP_{08} cladding mode (l = 0) [24].

IV. CONCLUSION

A wavelength-tunable ADM device for DWDM has been proposed, where the effect of chirp on the LPG transmission properties has been studied and illustrated with the aid of computer simulations. The chirped LPG produces spectra with wide bandwidth, and could be adjusted by varying the grating parameters and length. The FBG bonded on a fibre stretcher is tuned to obtain a desired wavelength channel by adjusting the applied voltage, and the remaining wavelength channels not selected could be added to the rest of the spectrum by using optical circulators.

The proposed OADM device is expected to have low insertion loss, low cross-talk, and high isolation, making it suitable for use in optical communication links. This ADM apparatus is the first known design of its kind, and promises to make a great impact in DWDM networks.

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REFERENCES


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