can obtain pulses '0', '0', '0', '0', '1', '0', '0', '0', '0', and '0' (pattern I) when not using the delay and pulses '0', '0', '0', '0', '1', '1', '0', '0', '0', and '0' (pattern II) when using the delay. The two patterns correspond to the 100Gbit/s OTDM signal. The pulselength of the OTDM signal is then broadened by using an optical fibre with a total chromatic dispersion of -60ps/nm. An 80km dispersion-shifted fibre (DSF) with a zero dispersion wavelength of 1552nm was used as the transmission fibre and the optical signal waveforms were measured before transmission (X) and after transmission (Y) with an optical sampling system [4]. Fig. 3a and b are the measured optical signal waveforms. The upper and lower Figures show the pattern I signal and pattern II signal respectively.

Fig. 2 Experimental setup

Fig. 3 Pulse shape
(i) Pattern I
(ii) Pattern II
a Before transmission (at point X of Fig. 2)
After transmission (at point Y of Fig. 2)

Fig. 4 Pulselength dependence of power penalty
100Gbit/s, pulselength before PB = 4ps, average power = +10dBm, signal wavelength = 1553nm, zero dispersion wavelength = 1552nm
0 SPM and inter-bit FWM (pattern II)
X SPM (pattern I)

From these results, it is clear that inter-bit FWM occurred only in the pattern II signal. We also numerically examined the influence of the single-pulse SPM-GVD effect and inter-bit FWM effect. In the simulation, we assumed that the optical signal had a repetition rate of 100Gbit/s, a pulselength of 4ps, an average input power of +10dBm, and a wavelength of 1553nm. The length and zero-dispersion wavelength of the transmission fibre were set at 80km and 1552nm, respectively. Fig. 4 depicts the relationship between the pulselength of the optical pulses and the power penalty caused by single-pulse SPM-GVD or inter-bit FWM. The power penalty is estimated using channel crosstalk. The channel crosstalk is defined as the ratio of the optical energy loss to the original signal energy in a time slot. The influence of SPM-GVD can be suppressed by broadening the pulse. In contrast, the influence of inter-bit FWM increases with the broadening of the pulselength. This is because the larger the pulselength becomes, the more the frequency components interact. This feature intensifies when the broadened pulselength is over the time slot. Therefore, there is an optimum pulselength: in the 100Gbit/s case, this is 6ps. This result indicates that pulse broadening is most effective when the pre-broadened pulselength is adjusted to this optimum value.

Conclusion: We showed that pulse broadening over the time slot causes inter-bit FWM, which degrades the OTDM transmission characteristics. We have also confirmed this effect experimentally by measuring OTDM signal waveforms, and have numerically estimated the magnitude of the effect. Adjusting the pulselength (to 6ps in the case of the 100Gbit/s case) is the best way to reduce the nonlinear effect in an optical fibre.

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References

Multichannel add/drop and cross-connect using fibre Bragg gratings and optical switches

Shien-Kuei Liaw, Keang-Po Ho and Sien Chi

A dynamically selective wavelength add/drop multiplexer (WADM) and a multilength wave cross-connect (M-XC) configuration for dense wavelength division multiplexed networks are proposed. Multiple channels add/drop and/or cross-connect can be realised according to the control of the optical switches and fibre Bragg gratings arrangement. The selective WADM and M-XC devices could provide more reconfigurable flexibility and survivability in WDM networks.

Introduction: Recently, significant research efforts have been devoted to the design of high-capacity, flexible, reliable and transparent multiwavelength optical networks [1, 2]. Wavelength add/drop multiplexer (WADM) and multilength wave cross-connect (M-XC) switches will play key roles in future optical dense wavelength division multiplexing (WDM) networks. The WADM is used for selectively dropping and inserting optical signals into the WDM network. It can reduce the processing load and latency in intermediate nodes by handling through-traffic. The closed related M-XC is configurable on a link-by-link basis to allow optimization of capacity allocation, management, and scalability of network size, especially in a reconfigurable ring topology.
Conventional optical WADMs usually consist of a $1 \times N$ demultiplexer (DMUX) followed by an $N \times 1$ multiplexer (MUX). A certain channel is dropped and/or added at each WADM unit according to a specific add-drop plan [3]. A wavelength selective (i.e. rearrangeable) M-XC can be implemented by adding a space division switch in between a WDM MUX/DMUX pair to select wavelengths and rearrange them in the spatial domain. This approach seems not to be very practical because the cost and noise associated with the optoelectronic repeater stages will make it difficult to construct a suitable electronic switch [4]. Recently, two system experiments for one-channel selective add-drop [5] and two-channel cross-connect [6] from trunk lines carrying several signals, by integrating some reflective fibre Bragg gratings (FBGs) according to a specific add-drop plan, were demonstrated. Though another WADM configuration based on FBGs and OSWs for simultaneous multiple wavelength add/drop via an FBG chain was also proposed [7], it seems less practical since the inclusion of multiple gratings would require an extra DMUX in the drop port and an extra MUX in the add port. In this Letter, we propose a WADM and M-XC configuration for simultaneous multiple wavelengths add/drop and cross-connect, respectively, by using FBGs, optical circulators (OCs) and OSWs.

Proposed configurations for WADM and M-XC: Fig. 1 shows a schematic diagram of the proposed wavelength-selective WADM device. One pair of a three-port OC and a $1 \times 2$ OSW are located at both the input and the output ports with $n$ ADM units cascading in sequence between them. Each ADM unit consists of one piece of FBG, with the central reflective wavelength matching the WDM signal $\lambda_i$ ($i = 1, 2, 3, \ldots, N$), one piece of single mode fibre (SMF), an $1 \times 2$ OSW and a three/four-port OC. The optical signals are launched into the first three-port OC at the left-hand side. Some of these OSW-pairs are switched to the FBG port(s) rather than the SMF port(s) for dropping and re-adding optical signal(s) with corresponding wavelength(s). For example, signal $i$ drops or passes through the cascading FBG chains depending on whether the corresponding $1 \times 2$ OSW pair is switched to FBG or SMF. When $\lambda_i$ drops from port three/four of the three/four-port OC, a new signal wavelength $\lambda_i'$ with the same central wavelength as $\lambda_i$ will add from port one of the four/three-port OC to the fibre link after it is reflected by FBG. Other optical signals not dropped by the desired FBG chains will pass through all the ADM units and then continue their forward propagation.

Fig. 2 shows the proposed configuration of the selective M-XC. $N$ cross-connect units, each consisting of one piece of FBG ($i = 1, 2, 3, \ldots, N$) matching the WDM channel signal $i$, a piece of SMF and a $1 \times 2$ OSW, are cascaded one by one and inserted in between the three-port OC and the $1 \times 2$ OSW pair. For example, by simultaneously switching some of these switch-pairs to the desired FBG ports such as FBG$_1$, and FBG$_4$, $\lambda_i$ and $\lambda_4$ of the upper fibre link will reflect and leave from port 3 of the OC1, continuing their forward propagation (termed here as passed-through) in the same fibre link. The channel signals other than $\lambda_1$ and $\lambda_4$ are spatially cross-connected (here, passed through the N cross-connect units) to the lower fibre link. Meanwhile, channel signals other than $\lambda_1'$ and $\lambda_4'$ of the lower fibre link are cross-connected to the upper fibre link. Thus, multiple channel cross-connection can be realised. There are two input ports (11 and 12) as well as two output ports (O1 and O2) in the M-XC configurations. These two input ports can operate in the same direction or in opposite directions (i.e. bidirectional) by simply re-arranging the lower three-port (number 1, 2 and 3) OC in the clockwise or anti-clockwise direction, dependent on the network structures in which the M-XC is located. The power loss for both WADM and M-XC configurations due to the cascading of fibre components and devices can be compensated easily by using optical amplifiers.

Experimental results of optical spectra: To investigate the feasibility of these proposed FBG and OSW-based WADM and M-XC, one set of four WDM channel signals ($\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$) with 1.3nm channel spacing in the 1.55-μm band are launched from port 1 of Fig. 1 and port II of Fig. 2 to demonstrate the one-wavelength drop (without re-add) and two-wavelength cross-connect functions, respectively. The inset of Fig. 1 shows the resulting output spectrum at point O of the pass-through signals for the WADM, and the inset of Fig. 2 shows the resulting output spectrum at point O2 of the cross-connect signals for the M-XC. The interport insertion loss of the OCs is less than 2dB and the insertion loss is 0.5dB for each OSW from the common port to any other ports, respectively. The isolation of each OC is $30 \pm 1 \text{dB}$ and the 3dB width of the FBGs used in these two experiments is $25 \pm 1 \text{nm}$ and $99\%$, respectively. In Fig. 1, one small spectral component contaminating the other three passed-through signals with $20 \text{dB}$ crosstalk level results from the 1% transmittivity of the FBGs. A similar result can also be found in Fig. 2. Further reduction in the crosstalk level for upgrading system performance is possible by improving the FBG reflectivity.

Conclusion: In summary, two configurations are proposed for multiple wavelengths add/drop and cross-connect based on FBGs and OSWs. The WADM and M-XC devices have potentially large add/drop efficiency, low channel crosstalk, uniform channel loss, high scalability and low cost, and hence may provide increased flexibility and survivability in WDM networks.

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Thermal decay of gratings written in hydrogen-loaded germanosilicate fibres

I. Riart and B. Pommellec

A new description of the thermal decay of gratings written in hydrogen-loaded germanosilicate fibres is proposed. This model allows an accurate prediction of lifetime.

The thermal stability of germanosilicate fibre Bragg gratings has now been heavily studied [1–5]. A model has been proposed [1] to describe thermal decay and to predict the lifetime of germanosilicate fibre Bragg gratings, leading to very good fits in the case of unloaded fibres [1, 2]. The model assumes that thermal decay follows a law of the type 1/(1 + Atα), where Tα is the time and A and α are two fitting constants. The mechanisms underlying this model postulate that carriers excited during writing are then trapped in a broad distribution of trap states and that the rate of thermal depopulation is a function of the trap depth. However, several authors [2–5] have found that this model does not completely apply to hydrogen (H2)-loaded fibres. Robert et al. [4] needed to use two distributions to account for short and long term decay, and Baker et al. [2] proposed a log-time based model to fit decay characteristics and predict lifetime. Kammann et al. [3] also observed a divergence in the case of H2-loaded fibres, and they suggest building an empirical curve by plotting all the normalised index modulations Δ𝑛(T) for the different temperatures according to the variable kBTln(T), in which k is the Boltzmann constant, T is the temperature, t is the time and v is a constant that allows them to predict long term behaviour.

Following the description of [2] and the approach of [3], we have plotted the normalised Δ𝑛(T) against kBTln(T), shown in Fig. 1. The gratings were written using an excimer laser emitting at 248nm with a fluence of ≈200mJ/cm2 at 10Hz. The grating length was 500μm. The photoinduced index modulation was 2×10−4; the studied temperatures were 175, 200, 250, 300, 350, 400 and 500°C, and three gratings were heated at each temperature. Based on the results from the authors mentioned, we expected the curves to be linear and shifted by a quantity equal to kBTln(v). Indeed, our curves are linear. Baker et al. [2] also noticed that at 85°C, there was no decay for a while. This could not be confirmed here since we did not perform any measurements at such low temperatures. A linear fit of these curves leads to a unique slope which is temperature independent. This slope is equal to −0.37 ± 0.05eV−1 (see Fig. 2). The origin ordinate, on the contrary, varies linearly with temperature. This could be expected since it contains a term proportional to kBTln(v). A linear fit yields (9.7 ± 0.5 × 10−1 in K−1) × (T in K) + 1.34 ± 0.03 (Fig. 2).

To further elucidate the interpretation of the coefficients and to determine the long term stability, it is necessary to use a correct distribution function associated with these results. In an attempt to find this distribution, we used the VAREPA model [6]. According to this model, a change of index during erasure occurs after a monomolecular reaction (A ↔ B) with a rate constant k. The expression for k is k = k0exp(−Ed/kBT), with k0 as the pre-exponential factor and E as the erasure activation energy. B is assumed to be the species responsible for the index change and A is the precursor. We use the idea of demarcation energy Ed below which the physico-chemical reaction corresponding to erasure is carried out. The remaining content of B after a time t and at a temperature T, assuming a saturated grating, is then given by

\[ [B](t) = A_0 \int_{E_{min}}^{E_{max}} g(E) dE \]  

where A0 is a constant and g is the distribution function for erasure. The expression of the demarcation energy is E = kBTln(k0t) [6]. After analysing the data, it appears that the distribution function must be a normalised constant distribution limited by E′′ and E′′′:

\[ g(E) = \begin{cases} 0 & E < E_{min} \\ \frac{1}{E_{max} - E_{min}} & E_{min} < E < E_{max} \\ 0 & E_{max} < E \end{cases} \]

(i) When E < E′′, the decay has not yet begun. This is the part observed by [2] at 85°C when the grating strength remained constant for a while. By replacing eqn. 2 in eqn. 1, we obtain [B](t) = A0. The erasure does not begin until a time corresponding to the time for E to reach E′′.

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