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Polarisation-insensitive wavelength converter based on cascaded nonlinearities in LiNbO$_3$ waveguides

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A polarisation-independent wavelength converter using cascaded nonlinearities in periodically-poled LiNbO$_3$ waveguides has been developed. The device uses a pump in the 1.5μm band, has negligible polarisation sensitivity and a penalty of < 0.5dB at 10Gbit/s.

Parametric wavelength conversion has a number of appealing properties such as data-format independence and quantum noise limited wavelength shifting. Traditional schemes for such devices have been dominated by parametric processes in nonlinear fibres, semiconductor optical amplifiers or nonlinear waveguides [1]. Recently, we introduced a new family of efficient wavelength converter devices based on a cascaded $\chi^{(2)}$ process in periodically-poled LiNbO$_3$ (PPLN) waveguides [2, 3]. In this process the pump at a frequency ω_P is doubled in the waveguide to $2\omega_P$; simultaneously, difference frequency mixing between the doubled pump at $2\omega_P$ with the channel at ω_S yields a shifted channel at $2\omega_P - \omega_S$. This process in essence mimics four-wave mixing (FWM) but with a much higher efficiency than that of FWM in fibres (efficiencies of > –10dB can be routinely achieved in devices shorter than 6cm).

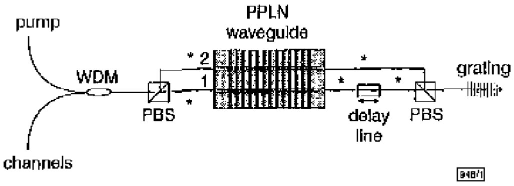

Fig. 1 *Schematic diagram of polarisation-insensitive wavelength converter module*

*: polarisation maintaining fibre

One common drawback to most parametric processes is their dependence on polarisation. This dependence has been eliminated in the past using a number of schemes [4, 5]. In this Letter we present one successful solution to the removal of this polarisation dependence in wavelength converters that use PPLN waveguides.

Fig. 1 shows a schematic diagram of the proposed implementation. All the components are fibre-based or fibre-coupled and thus robustness is assured. The incoming channels are combined with the pump in a wavelength-division multiplexing (WDM) coupler. The co-propagating channels and pump are polarisation-split in a fibre-coupled polarisation beam splitter cube (PBS). These two outputs are carried through polarisation-maintaining (PM) fibre (Panda) and are later pigtailed onto two independent but identical waveguides that have the same phase matching wavelengths (1552nm at 120°C). The fibres are properly aligned to the waveguide in order to match the TM polarisation that the waveguide favours. The PPLN waveguides are 5.5cm long and were fabricated using annealed proton exchange. The details of the fabrication have been described elsewhere [2]. The waveguides include input and output taper sections that improve the fibre coupling efficiency. Their typical fibre-to-fibre loss is between 3 and 4dB. The outputs of the waveguides are also pigtailed to PM fibre and recombined in an identical PBS cube. A variable, fibre-coupled delay line in one arm compensates for the difference in

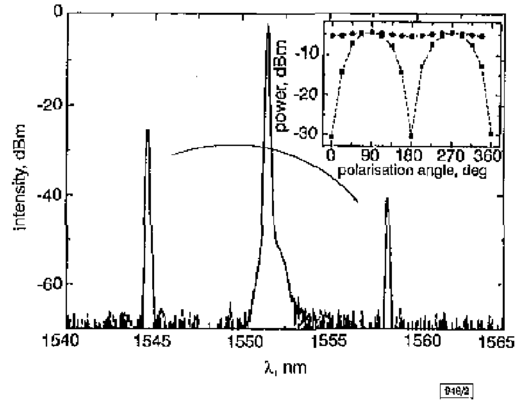

Fig. 2 *Wavelength conversion performance for one channel only and for both polarisations*

Pump power is ~100mW per polarisation and conversion bandwidth is ~70nm
– – – – polarisation 1
——— polarisation 2
Inset: polarisation dependence of linear transmission
■ one waveguide connected
● both waveguides connected

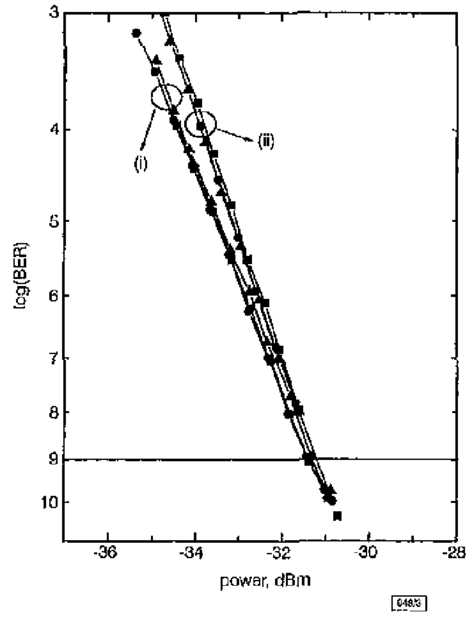

Fig. 3 *Bit error rate measurements for converting single channel as shown in Fig. 2*

Data format: PRBS, $2^{31}-1$, 10Gbit/s
(i) back-to-back
(ii) converted
■ polarisation 1
● polarisation 2
▲ 50% power in each polarisation

delay experienced by the two polarisations. The overall loss from the input to the WDM coupler to the overall output is slightly less than 5dB, with a polarisation sensitivity or loss (PDL) of between 1 and 0.5dB. The latter is due to the accumulation of PDL in the PBS cubes and the use of the delay line in one of the arms. This PDL can be eliminated by proper pre-adjustment of the pump polarisation so that the wavelength conversion process has exactly the reverse PDL as the linear transmission through the waveguide. The polarisation dependence of the linear transmission is shown in the inset of Fig. 2, which also shows the typical wavelength conversion performance for one channel only, and for both polarisations. The pump polarisation was adjusted as mentioned before, and thus the PDL of the converted channel is almost negligible. The conversion efficiency is very similar to that published before, i.e. –15 (–10) dB external efficiency for a pump power (per polarisation) of 100 (150) mW [2]. Fig. 2 shows conversion with only 100mW per polarisation.

We then measured the bit error rate at 10Gbit/s (PRBS data, $10^{31} - 1$) when the converter was running with a single channel, and for three different combinations of polarisations. These combinations were achieved using a fibre polarisation rotator so that the incoming channel travelled: (i) 100% through waveguide 1, (ii) 100% through waveguide 2 or (iii) 50% through each waveguide. The latter case maximises the possible penalties due to any residual polarisation beating. These curves are shown in Fig. 3. The baseline for the BER curves is measured when the signal wavelength is tuned to 1558.5nm. As can be seen in Fig. 3, the penalty after wavelength conversion is < 0.5dB, and no appreciable difference is observed for all the different polarisation combinations.

In summary, we have developed a high efficiency polarisation insensitive wavelength converter based on periodically-poled $LiNbO_3$ waveguides. This converter has an external efficiency of –10dB and negligible polarisation dependence when the residual PDL is compensated for by a proper choice of the pump polarisation. This converter is background noise free and the penalty when converting a single channel was < 0.5dB. This device can be also used as a polarisation-independent spectral inverter in dense WDM transmission systems, with the purpose of compensating for dispersion and/or nonlinearities [6].

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Reconfigurable optical cross-connect using WDM MUX/DEMUX pair and tunable fibre Bragg gratings

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A reconfigurable 2 × 2 optical cross-connect (OXC) based on a WDM MUX/DEMUX pair and tunable fibre Bragg gratings (FBGs) is proposed. It has the advantage of uniform insertion loss and a reduction of the number of MUX/DEMUXs required. The cross-connect operation of the proposed OXC in the optical spectra domain has been experimentally demonstrated.

Introduction: In future all-optical wavelength division multiplexing (WDM) networks, reconfigurable optical cross-connects (OXCs) will play a key role in improving the flexibility of the networks [1]. A conventional reconfigurable OXC can be implemented by inserting a space division switch between WDM multiplexer (MUX) and demultiplexer (DEMUX) pairs [1]. Recently, a reconfigurable 2 × 2 OXC based on fibre Bragg gratings (FBGs) and optical switches (OSWs) was proposed [2]. However, in this configuration of the OXC, the in-line loss of each wavelength channel is not uniform because the path length of each wavelength channel reflected by the FBG is different and the reflected channel experiences different insertion losses for the FBGs and OSWs. In this Letter, we propose a reconfigurable 2 × 2 OXC using a WDM MUX and DEMUX pair and tunable FBGs. The proposed OXC is inherently free from differences in the in-line loss of each wavelength channel. Compared to the conventional reconfigurable OXC, the proposed OXC also reduces the number of MUX and DEMUX pairs.

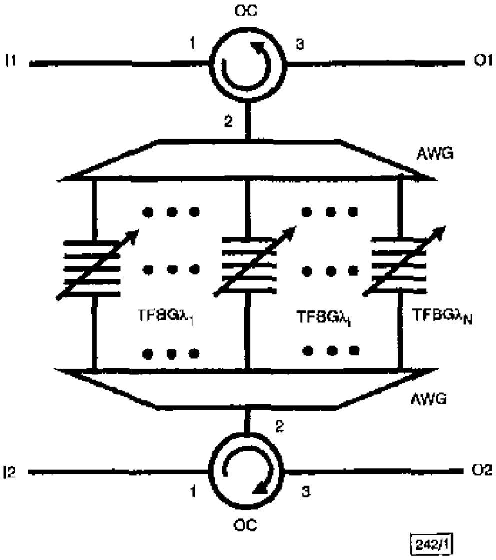

Fig. 1 *Schematic diagram of proposed 2 × 2 OXC*

TFBG: tunable fibre Bragg grating

OXC configurations: A schematic diagram of the proposed 2 × 2 OXC is shown in Fig. 1. There are two input ports, I1 and I2, and two output ports, O1 and O2. An arrayed waveguide grating (AWG) can be used as a wavelength MUX or DEMUX. Wavelength channels coming from I1 are demultiplexed by the upper AWG. Each output port (λ_i layer) has a tunable FBG in which the centre wavelength can be matched to the channel wavelength of the AWGs. We can determine the connection state of the OXC by tuning the centre wavelength of the FBG. When the centre wavelength of the FBG is matched to the wavelength of the λ_i layer, then the wavelength channel is reflected by the FBG. The reflected wavelength channel is multiplexed by the upper AWG and then travels back to O1. This case is called the passing state of wavelength channel λ_i. When the centre wavelength of the FBG is set to be different from the wavelength of the λ_i layer by tuning the centre wavelength of the FBG, then the wavelength channel passes through the FBG, is multiplexed by the lower AWG, and arrives