noise, timing jitter and wavelength jitter resulting in a soliton transmission system that requires neither narrowband optical filters nor retiming modulators to span transoceanic distances with significant system margin.

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Undoing of soliton interaction by optical phase conjugation

S. Wen and S. Chi

Indexing terms: Soliton transmission, Solitons, Optical phase conjugation

The undoing of soliton interaction by optical phase conjugation in the presence of third-order dispersion and fibre loss which is compensated for by optical amplifiers are studied. If the conjugator is applied before there are significant changes in the pulse shapes, the soliton interaction can be undone well.

Recent experiments show that chromatic dispersion can be compensated for by optical phase conjugation (OPC) [1, 2]. In fact, the theory was proposed more than a decade ago [3]. In addition to chromatic dispersion, the effects of self-phase modulation (SPM) and self-frequency shift (SFS) can also be recovered by OPC in the lossless case [4]. Because the optical soliton is a result of the second-order dispersion and SPM, the soliton effects in the lossless case can be recovered by OPC. In this Letter, we will show undoing of the soliton interaction by OPC, where the fibre loss is compensated for by optical amplifiers.

The wave equation which describes soliton propagation in singlemode fibre can be written as

$$i\frac{\partial\phi}{\partial z}-\frac{1}{2}\beta_2\frac{\partial^2\phi}{\partial\tau^2}-i\frac{1}{6}\beta_3\frac{\partial^3\phi}{\partial\tau^3}+\gamma|\phi|^2\phi-c_r\frac{\partial|\phi|^2}{\partial\tau}\phi=-\frac{1}{2}i\alpha\phi \quad (1)$$

where β_2 and β_3 represent the second-order and third-order dispersions, respectively. $\gamma = n_2\beta_0/A_{eff}$, where n_2 is the Kerr coefficient and A_{eff} is the effective fibre cross-section, c_r is the coefficient of the self-frequency shift (SFS), and α is the fibre loss. From eqn. 1, when $\beta_3 = \alpha = 0$, it can be proved that the effects of second-order dispersion, SPM, and SFS can be completely recovered by OPC [4, 6]. Therefore, in lossless fibre without third-order dispersion, the soliton interaction can be undone by OPC even in the presence of SFS. However, when the pulse width is short or the soliton wavelength is near the zero-dispersion wavelength, the effect of third-order dispersion becomes significant. In the following, the effect of third-order dispersion on the undoing of soliton interaction by OPC is described. The soliton wavelength is assumed to be 1.55 µm. The coefficients in eqn. 1 are taken as $\beta_2 = -0.64\,ps^2/km$ (0.5 ps/km/nm), $\beta_3 = 0.074\,ps^3/km$, $n_2 = 3.2 \times 10^{-20}\,m^2/W$, $A_{eff} = 35\,\mu m^2$, and $c_r = 3.85 \times 10^{-16}\,ps\ m/W$. To reduce the soliton power variation, the fibre loss is compensated for by distributed erbium-doped fibre amplifiers (DEDFAs), which are pumped bidirectionally with 1.48µm pump wavelength [5]. Both the intrinsic fibre losses at the soliton wavelength and pump wavelength are assumed to be 0.23dB/km. The doping density of the erbium-doped fibre is taken as $2.6 \times 10^{21}\,m^{-3}$. The other parameters of the DEDFA are the same as given in [5]. The length of the amplifier is taken to be 30km. The considered soliton pulse width is 5ps and the soliton separation is five pulse widths. We notice that, because the soliton period is only 19.8km for 5ps pulse width, small power perturbation is required for stable soliton transmission. The maximum soliton power variation in the DEDFA is only 2.3% and the required pump power is 34.6mW.

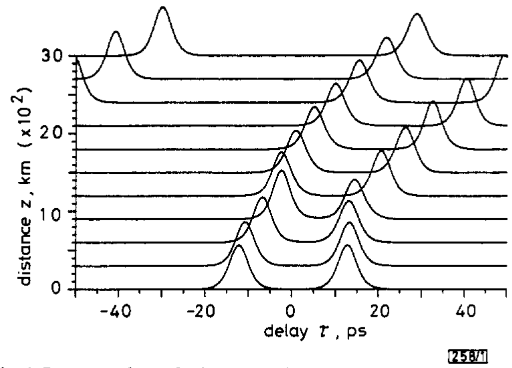

Fig. 1 *Power envelope of soliton pair along cascaded DEDFAs*

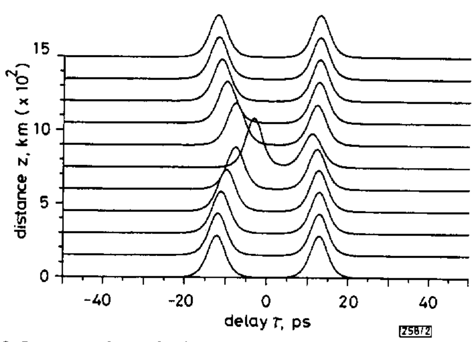

Fig. 2 *Power envelope of soliton pair along lossless fibre without third order*

An optical phase conjugator is applied at 750km

Fig. 1 shows the evolution of the soliton pair along the cascaded DEDFAs. It is seen that the two solitons attract each other and then repel after propagating ~810km. When the two solitons come close, there is energy exchange between them through the SFS. In the lossless case without third-order dispersion and SFS, the two solitons collide at 814km. The repulsion of the two solitons shown in Fig. 1 is mainly due to the effect of SFS because the powers of the two solitons are different through the interaction, and their group velocities are different due to SFS. By using OPC to undo the soliton interaction, the location of the optical phase conjugator is important. In the lossless case without third-order dispersion, the conjugator can be applied anywhere because any effect governed by eqn. 1 can be recovered. From the theory of OPC, the effects on the solitons which propagate some distance can be recovered by the conjugate solitons which propagate the same distance. For example, Fig. 2 shows the undoing of soliton interaction in the lossless case without third-order dispersion. In Fig. 2, an ideal conjugator is applied at 750km where both the pulse shapes of the solitons have changed seriously. From Fig. 2, the undoing is complete at 1500 km. For the real case shown in Fig. 1, if the conjugator is applied at the same distance shown in Fig. 2, the soliton interaction cannot be undone as effectively, which is shown in Fig. 3. If the conjugator is applied at the distance where the pulse shapes of the two solitons have not yet significantly changed, the soliton interaction can be undone well. Fig. 4 shows the undoing of soliton interaction when the conjugator is applied at 600km for the real case shown in Fig. 1. It is seen that, except for a net change of the time delay, both the pulse shapes and separation of the two solitons almost recover at 1200 km. The net change of the time delay is the effect of the third-order dispersion on the transmission of the soliton pair. If the conjugator is applied after the interaction, the repulsion of the two solitons is even more serious than the case without the conjugator. When the lumped amplifier is used to compensate for the fibre loss, it is found that the soliton interaction can also be undone by OPC but the pulse width must be long enough so that the soliton is stable. This shows that, even when the soliton power is perturbed, the soliton interaction in the presence of third-order dispersion can be undone by OPC if the pulse shapes of the solitons do not significantly change before the conjugator is applied.

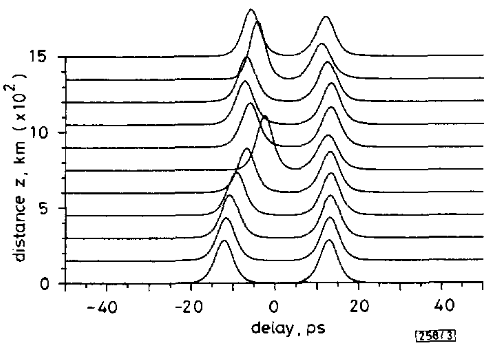

Fig. 3 *Power envelope of soliton pair along cascaded DEDFAs*

An optical phase conjugator is applied at 750km

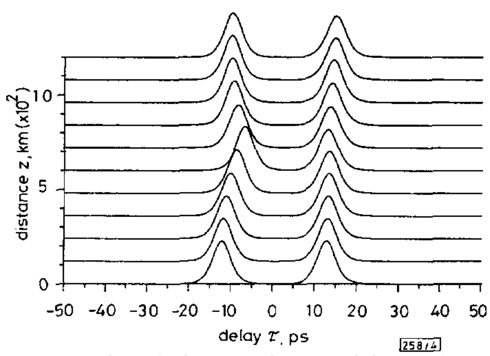

Fig. 4 *Power envelope of soliton pair along cascaded DEDFAs*

An optical phase conjugator is applied at 600km

In conclusion, the undoing of the soliton interaction by OPC is investigated. In the lossless fibre without third-order dispersion, the soliton interaction can be perfectly recovered. With the third-order dispersion and the fibre loss compensated for by the optical amplifiers, if the conjugator is applied before there are significant changes in the pulse shapes, the soliton interaction can also be undone effectively.

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Wavelength precision of monolithic InP grating multiplexer/demultiplexers

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Indexing terms: Wavelength division multiplexing, Grating filters

The authors examine the wavelength precision of InP/InGaAsP/InP planar waveguide grating multiplexer/demultiplexers, the sources of wavelength error and the limitations they impose on practical devices. The performance of MUX/DEMUXs fabricated from 2 inch MOCVD wafers is reported, demonstrating absolute wavelength control better than ±7nm and channel-to-channel variation of < ±0.03nm.

Introduction: Wavelength division multiplexed (WDM) networks are being developed for future broadband telecommunications and computer systems [1]. The optoelectronic components required must possess a high degree of wavelength precision and stability, which presents a severe challenge to the development of suitable components.

An InP technology being investigated for its potential to provide a number of different WDM functions is that based on a monolithic grating multiplexer/demultiplexer (MUX/DEMUX) [2, 3], which is in essence, a two-dimensional grating 'spectrometer' that may be integrated with active elements to form devices such as multi-λ lasers [4] and detectors [5, 6]. This Letter examines the wavelength precision of the component. The performance of MUX/DEMUXs formed from different 2inch metal organic chemical vapour deposition (MOCVD) grown wafers is presented and compared with expectations.

Sources of wavelength error: A typical MUX/DEMUX is illustrated in Fig. 1. A curved grating focuses light from an input to an output guide according to the diffraction equation

$$d(\sin\theta_i + \sin\theta_r) = p\lambda_0/N \qquad (1)$$

where d is the grating spacing (a constant projected on the tangent to the pole in the typical Rowland circle construction [2]), p the diffraction order, and N the effective index for the guided light, β/k_0. The wavelength precision is determined by the accuracy with which the parameters in eqn. 1 may be realised in practice.