References


Transmission of dispersion-managed solitons at 20Gbit/s over 20000km


The transmission of 20Gbit/s data over distances of 20000km was achieved using dispersion-managed solitons without significant impairment due to pulse-to-pulse interactions. Error rates of < 10^-4 were achieved over the entire distance measured.

Since the first demonstration of high bit rate long distance propagation using dispersion-managed solitons [1], an intense research effort has been underway to determine the properties of these nonlinear pulses. In particular there have been theoretical investigations of soliton-soliton interactions in dispersion-managed soliton systems and their potential to limit dispersion-managed soliton transmission [2, 3]. Recent theoretical results indicate that, for certain two-step dispersion maps, these interactions may limit a transmission system with an initial pulse spacing of 50ps, corresponding to 20Gbit/s data rates, to distances of the order of 10000km or less [4, 5]. Our initial experiments at 20Gbit/s and our analysis show that a far more serious limitation of the transmission distance can be caused by excess energy in the tails of the initial pulses which lowers the extinction ratio. By using initial pulses with rapidly decreasing tails along with careful system design and implementation, we transmitted 20Gbit/s data over 20000km at a measured error rate < 10^-4 without significant impairment due to pulse-to-pulse interactions. This system was ultimately limited by noise growth in the space. We have modelled these results using a Monte Carlo simulation, achieving excellent agreement with the measured data. The propagation distance achieved exceeds previously reported single channel dispersion-managed soliton results at 20Gbit/s by > 40% [1].

The experiments used the same recirculating loop, dispersion map, and an in-line 2.8nm bandpass filter reported in [6]. The map consisted of 100km of fibre with a dispersion of ~1.1ps/nm km at 1551nm followed by 7km of fibre with a dispersion of +16.7ps/nm km at 1551nm. The path-averaged dispersion was ~+0.03ps/nm km (anomalous). The data source was a commercially available synchronously modeled fibre laser operating at 10GHz. The pulses were encoded with a 2^11 - 1 pseudorandom bit pattern. The data stream was divided into two streams and recombinet with a relative delay between the streams of ~150ps to produce 20Gbit/s data. By adjusting the power in the optical amplifiers we kept the same equilibrium pulse characteristics as in our previous 10Gbit/s experiments [7]. The pulse energy averaged over the map is 0.06pJ and within the map the pulse has a bandwidth of 0.45nm with a minimum and maximum pulsewidth of 9 and 22ps, respectively.

Fig. 1 Measured eye diagram of 20Gbit/s data stream at input of transmission experiment
Horizontal scale: 50ps/div

Fig. 2 Measured eye diagram of 20Gbit/s data stream demultiplexed to 10Gbit/s
a At 6km
b At 20000km transmission distance
Horizontal scale: 50ps/div

Fig. 3 shows the decision level of the bit error rate tester at an error rate of 10^-4 as a function of distance, along with the simulation [9] showing excellent agreement. These data show that the
build-up of amplified spontaneous emission in the spaces limits transmission as was the case in the 10Gbit/s data [6]. From our previous measurements [7] and estimate of the 20Gbit/s demultiplexed timing window we conclude that timing jitter is not a limitation on the transmission of the 20Gbit/s data at distances up to 20000km. In [6] an intra-loop acousto-optic frequency shifter cancelled out the 100MHz frequency shift of the acousto-optic switch that closes the loop. The shifter was unavailable for the experiments described in this Letter, leaving us with a net 100MHz frequency shift per 107km of propagation distance. As the simulation indicates, the effect of this frequency shift, which is equivalent to frequency sliding filters, is to reduce the build-up of the ASE at distances greater than 20000km. However, taking into account the loop coupling losses (= 7dB), the simulation indicates that in a straight-line system having no net frequency shift a bit-error rate < 10 -6 at distances up to 20000km would still be achieved.

Fig. 3 Measured and simulated threshold of bit error rate tester at constant bit error rate of 10 -6

marks
spaces
--- simulation for frequency sliding
--- --- simulation for no frequency sliding

In conclusion, we have propagated dispersion-managed solitons at a data rate of 20Gbit/s with an error-rate of < 10 -6 over a distance of 20000km without observing any significant impairment due to pulse-to-pulse interactions. We have carried out a numerical simulation of our experiment and achieved excellent agreement with the data.

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References

Slanted gratings UV-written in photosensitive cladding fibre

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Experimental results concerning slanted gratings photo-written in a photosensitive cladding fibre and in a standard step index fibre are presented. The improvements concerning back reflection for an FWHM bandwidth suitable for erbium-doped fibre amplifier gain equalisation are demonstrated in the case of slanted gratings realised within photosensitive cladding fibre.

Introduction: The use of filters to flatten the gain spectrum of erbium-doped fibre amplifiers (EDFAs) has great interest for dense wavelength division multiplexing (DWDM) systems. Recently, long period gratings (LPGs) have been used in such systems [1]; however, their strong temperature sensitivity (ΔT = 50°C/m) and the difficulty in developing a passive system to thermally stabilise the centre wavelength makes LPGs difficult to use in gain flattening operations.

Slanted gratings (SGs) have a lower temperature sensitivity than LPGs (ΔT = 12°C/m), and can easily be thermally stabilised. However, the limitation of these filters is the residual back reflection level [2]. Indeed, it is always a serious drawback if these components have to be incorporated in amplifier modules because they can lead to a degradation in noise figure. To reduce this back reflection, we have realised SGs in a photosensitive cladding fibre manufactured in our laboratories [3]. We present in this Letter a comparison between the features of slanted gratings realised in a standard step index fibre and in a photosensitive cladding fibre.

Analysis: During the writing process of a Bragg grating, a coupling between the fundamental mode and the cladding modes occurs. The coupling efficiency depends on the photoinduced index change Δn, the spatial overlap of the excited modes and the angle θ defined in [4] between the UV fringes and the cross-section of the fibre. Propagation constants must satisfy the following phase matching conditions:

βLPO1 + β = \frac{2π}{λ} \cos θ

Where \β_{LPO1} and β are, respectively, the propagation constants of mode LP_01 and cladding modes, λ is the grating pitch and θ the blazing angle.

According to coupled-mode theory [5], the level of back reflection R, measured with an optical spectrum analyser at resonance,