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High-quality, soliton loss-compensation in a 38km dispersion decreasing fibre

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Abstract

We report the fabrication of a 38 km soliton loss-compensating, dispersion decreasing fibre with an exponential dispersion profile accurately matched to the fibre loss. High quality, loss compensation for 3.5 ps soliton pulses over 38 km (≈19 soliton periods) is demonstrated for the first time to our knowledge.

Keywords
Solitons, Dispersion, Soliton communications, Nonlinear optics

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The discovery of the erbium-doped fibre amplifier and more recently the development of advanced soliton control techniques has led to rapid advances is soliton transmission experiments. However, access to bit-rates >40 Gbit/s is restricted by the periodic amplification process once the soliton period (z_0) approaches that of the amplifier spacing [1,2]. In this regime the perturbation to the pulses due to the fibre loss becomes too severe resulting in a violation of 'average' soliton dynamics and eventual decay of the pulses [3]. The perturbation can only be eliminated by ensuring that the dispersive and nonlinear effects balance at all points along the fibre despite the presence of background optical loss. This can be achieved either by using a distributed EDFA to cancel the local fibre loss [4], or by the use of a Loss Compensating Dispersion Decreasing Fibre (LCDDF) [5]. In the later case the dispersion of the transmission fibre is made to fall exponentially along its length so as to exactly follow the decrease in intensity and hence the strength of the nonlinear interaction thus ensuring a balance between the two effects at all points along the fibre. To date, most experimental effort has centered on the use of distributed amplifiers [4]. Recently improved transmission of 1-2 ps pulses over a 40 km dispersion varying fibre span has been reported renewing interest in the LCDDF option [6]. Unfortunately, the dispersion variation of the fibre in these experiments did not follow the loss profile so that although improved pulse transmission was indeed obtained true loss compensation was not demonstrated. In this letter we report the fabrication of a 38 km LCDDF with a dispersion profile closely matched to the fibre loss. Furthermore we demonstrate for the first time to our knowledge soliton loss compensation for 3.5 ps pulses over a 38 km span (19 soliton periods).

The LCDDF was fabricated from a step-index preform of NA=0.165 and designed to give a 125 μm single-mode fibre cut-off wavelength of 1310 nm. The preform had excellent homogeneity along its length. The required dispersion variation was obtained by tapering the fibre during the pulling process. The exact fibre diameter variation required to achieve complete loss compensation over 38 km of fibre was evaluated for an input dispersion of 6.0 ps/(nm.km). A second order correction to compensate for the ~5% mode-area variation was included. The fibre was pulled in two sections (LCDDF1 and LCDDF2) that could either be used individually, or spliced together to give the full 38km span. The first section had a length of 20 km (dispersion variation based on fibre loss = 0.27 dB/km) and the second section a length of 18km (dispersion based on fibre loss = 0.26 dB/km). An OTDR plot of the actual fibre losses with the superposed design loss profiles are illustrated in Figs.1a and b. The two glitches ($\approx$0.3 dB additional loss over lengths of 200m) observed in the measured loss profiles were due to localised imperfections within the preform cladding and resulted in slight deviations from the desired form. The total deviation at any point within the fibres was however small ($< +/-$ 0.2 dB) with the average loss matching almost exactly in the case of LCCDF1 and within 0.2 dB within LCDDF2. The mismatch over the full 38 km was therefore 0.2 dB in 10.1 dB. The dispersion of LCDDF1 was set to vary exponentially from 6ps/nm.km at the input to 1.75 ps/nm.km at the output (corresponding to 5.4 dB loss) and from 1.75 ps/(nm.km) to 0.65 ps/(nm.km) (loss = 4.7 dB) in LCDDF2. The required external fibre diameter variation was from 105-96 μm in LCDDF1 and from 96 μm to 92 μm in LCDDF2. The RMS dispersion variation along the fibre length was <0.1 ps/(nm.km) as determined from measurements of the RMS diameter error (0.18μm). Measurements of the dispersion at the beginning and end of the two fibres along with average measurements along the two spans were in excellent agreement (+/- 0.1 ps/nm/km) with our target values. The third order dispersion within the fibre was measured to be 0.053 ps/(nm^2.km) and polarisation mode dispersion $\approx$ 0.1 ps/km$^{0.5}$.

Transform-limited, soliton pulses from a polarisation-switch fibre laser with durations in the range 1.5-16 ps, and tunable centre wavelength in the range 1550-1565nm, were input into the LCDDF via an EDFA. The EDFA permitted us to vary the power launched into the LCDDF so as to match it to that corresponding to the fundamental soliton. A second EDFA was placed at the LCCDF output to boost the signal level prior to autocorrelation and spectral measurement.

Soliton loss compensation was obtained for a wide range of pulse durations in both single LCDDF sections and in the composite system. In Fig.2 we show the results of 3.5 ps pulse transmission over the complete (38 km) system (LCDDF1 + LCDDF2). At low powers the pulse simply broadened linearly with no spectral distortion. However, as the input pulse powers were gradually raised so as to correspond to soliton orders $N>0.5$, distinct spectral narrowing and side-band generation was obtained due to the imperfect balance between dispersion and nonlinearity at all points along the fibre. Such behaviour was expected from our numerical simulations of the system. The spectral distortion decreases as the fundamental soliton power is approached and the output pulse duration approaches that of the input. The autocorrelations and spectra for input $N=1$ pulses at 0, 20 and 38 km are illustrated in Figs.3.a-c . It is seen that the solitons are successfully transmitted over the fibre length with minimal temporal distortion. The fibre span is equivalent to $\approx 19\ z_0$ in this instance. A small degree of spectral distortion is apparent at both 20 and 38 km due to the slight mismatch in nonlinearity and dispersion at all points along the fibre length. The maximum deviation is $<$ 1dB over a 4nm bandwidth (pulse spectral halfwidth = 0.74nm) and confirms the quality of the loss compensation (see Fig.3). For longer pulses $>$ 5ps ($L_{LCDDF} < 10z_0$) both spectral and temporal distortion could be eliminated.

In conclusion, we have demonstrated the fabrication of a 38 km LCDDF. All of our experimental evidence indicates that an excellent match of the LCDDF dispersion variation to loss profile has been obtained. The LCDDF quality has been confirmed in a series of single pulse propagation experiments. We report fundamental soliton propagation of 3.5ps pulses over 19 z_0 (38 km). Our results clearly indicate that high-quality, soliton loss compensation can be achieved for a total distributed loss of ≈ 10 dB (40 km of fibre) and illustrate the possibility of amplifer spacings of > = 20 soliton periods for use in ultra-high speed transmission lines. With care, scaling of the dispersion characteristics of our fibre by ≈ 1/5 thereby reducing the average dispersion of the fibre to ≈0.5 ps/(nm.km) should be possible. This should help reduce Gordon-Haus jitter, Soliton-Self-Frequency Shift (SSFS) and soliton interaction effects (for a given physical transmission distance), and lower the optical power requirements - key considerations for any practical LCDDF based system.

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Fig.1 Experimental OTDR plot illustrating loss within LCDDF1 and LCDDF2 with superposed design loss profiles.

Fig.2 Spectra and autocorrelation plots of 3.5ps, N = 1 solitons at (a) system input (0 km), (b) output of LCDDF1 (20 km) and (c) at output of LCDDF2 (38 km). Marked pulsed widths are deconvolved pulse halfwidths.

Fig.3 Logarithmic plot illustrating deviation in pulse output spectra (38km) from input spectra (0 km) across full spectral bandwidth for 3.5 ps pulse propagation.

Fig 1.

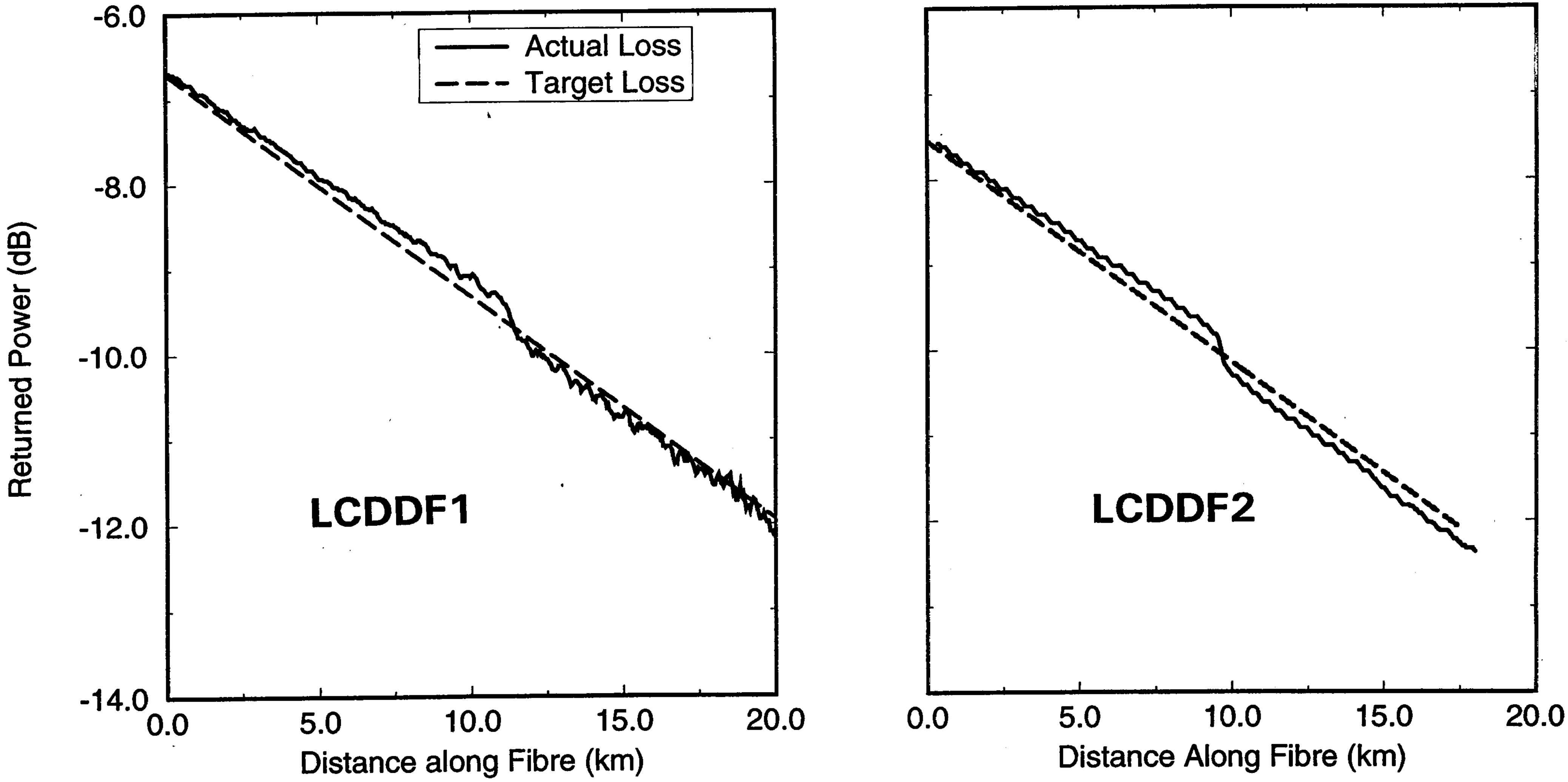

Actual Loss
Target Loss
Returned Power (dB)
-6.0
-8.0
-10.0
-12.0
-14.0
0.0
5.0
10.0
15.0
20.0
Distance along Fibre (km)
LCDDF1
0.0
5.0
10.0
15.0
20.0
Distance Along Fibre (km)
LCDDF2

Fig 2.

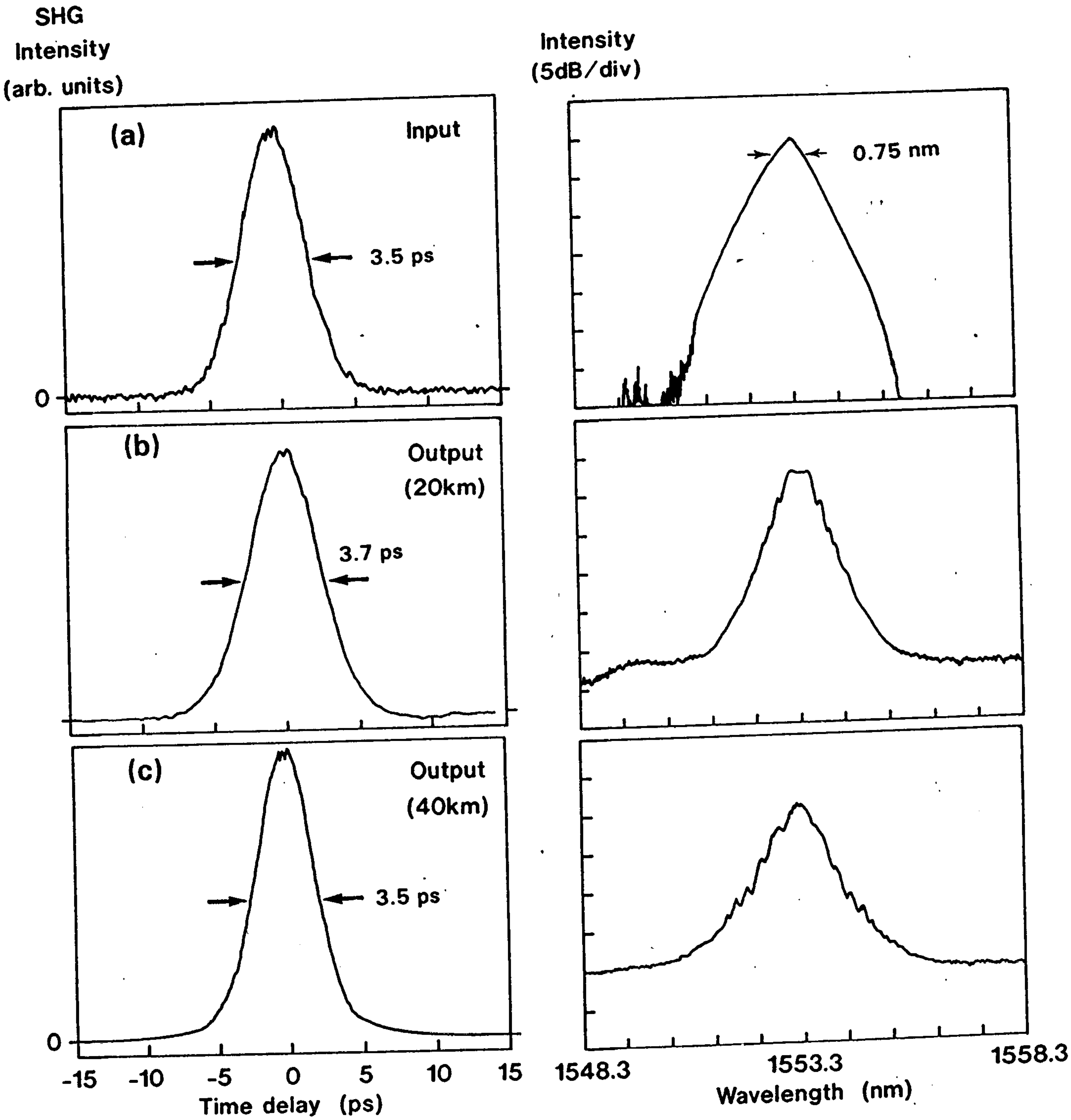
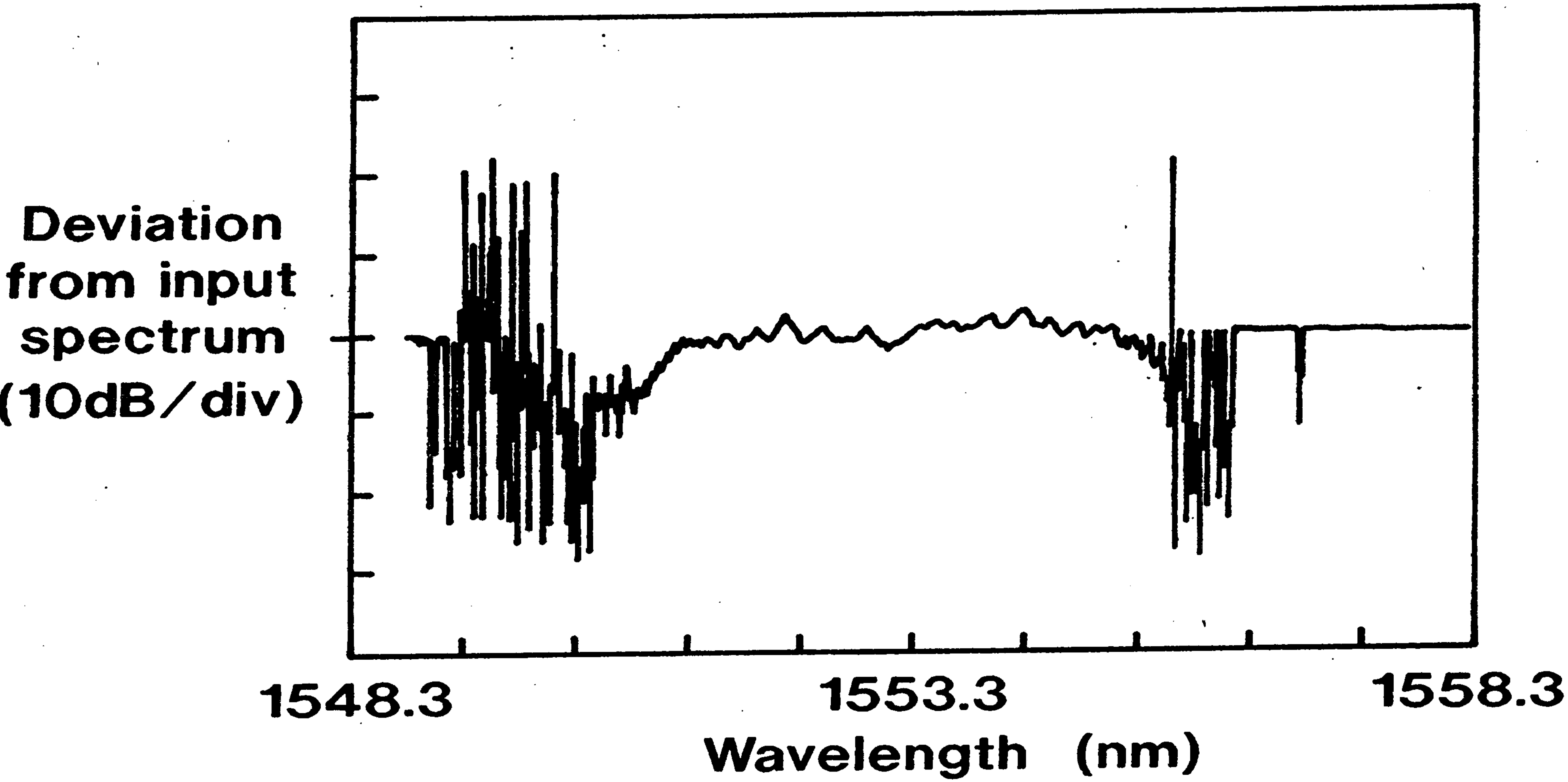

SHG
Intensity
(arb. units)
Intensity
(5dB/div)
(a)
Input
3.5 ps
0.75 nm
0
(b)
Output
(20km)
3.7 ps
(c)
Output
(40km)
3.5 ps
0
-15
-10
-5
0
5
10
15
Time delay (ps)
1548.3
1553.3
1558.3
Wavelength (nm)

Fig 3


Deviation from input spectrum (10dB/div)
1548.3
1553.3
1558.3
Wavelength (nm)