the performance of the proposed technique is affected by the neighbouring channel only. In the previously proposed techniques using pilot tones, the ghost tones of every WDM channel (caused by EDFA cross-gain modulation) accumulated and could result in significant errors since all the WDM channels were monitored simultaneously by using a single photodetector [5, 6]. Consequently, the effects of EDFA cross-gain modulation increased with the number of WDM channels. Conversely, the scalability of the proposed technique would not be limited by the number of WDM channels.

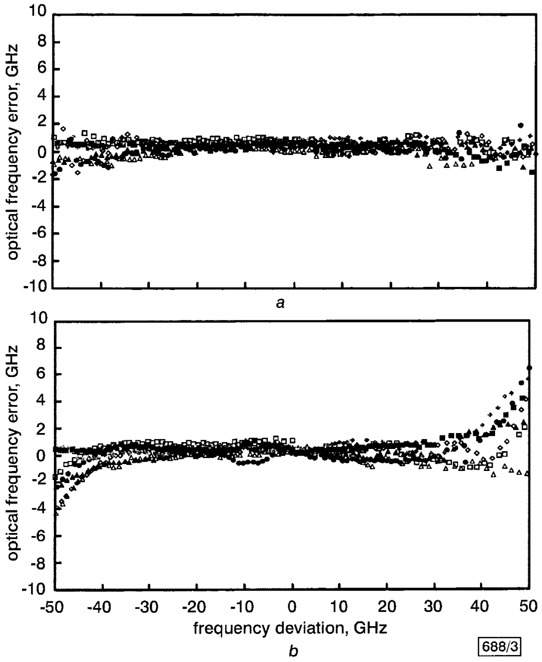

Fig. 3 *Measured frequency errors of seven 10 Gbit/s channels before and after transmission over 640 km of singlemode fibre*

a Before transmission
b After transmission

Conclusion: We have demonstrated a simple technique to monitor the optical frequencies of WDM channels. The proposed technique was implemented by using pilot tones, an AWG, an array of photodetectors, an A/D converter and a processor for FFT. The results show that the optical frequencies of multiple WDM channels can be monitored simultaneously with accuracy better than ±2 GHz even after transmission over 640 km of SMF. In addition, unlike the previous pilot tone based monitoring techniques, the proposed technique was almost insensitive to the cross-gain modulation of the EDFA. As a result, the scalability of the proposed technique would not be limited by the number of WDM channels.

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Optical pulse intensity and phase measurement by time-to-space conversion based on time-lens operation

N.K. Berger, B. Levit and B. Fischer

A method for measuring the phase profile of optical pulses, based on time-to-space conversion by a time lens, is presented. Experimental results are shown for semiconductor laser pulses.

Introduction: There has been much recent interest in methods for characterising short optical pulses. Temporal [1] and spectral [2, 3] interferometry that were used for this purpose, enabled simplification and reduction of the processing time as well as a substantial increase of the sensitivity for light intensity. Other methods that allowed real-time characterisation of optical pulses were based on time-lens operation [4 – 8], with the advantage of a direct measurement of pulse intensity profiles without any mathematical processing, e.g. a time-to-frequency converter was suggested [5] for measuring the intensity profile of picosecond pulses. Similar ideas were implemented for optical pulse gating [6], for spectro-temporal imaging of Ti-sapphire laser pulses [7], and for controlling the pulse shape of semiconductor lasers [8]. The time-lens operation in these works was performed using several methods, such as an electrooptic phase modulator [5, 8], multiplication of the original pulse with a chirped pulse by sum-frequency generation [4, 6], and cross-phase modulation of the original pulse with an intense pump pulse in a nonlinear fibre [7]. Different elements were used as delay lines: diffraction gratings [4 – 6], prisms [7], and singlemode optical fibres [8]. In all these works, which are based on time-lens operation, only the intensity of the pulses was measured.

In the present work we demonstrate the ability to measure both the intensity and the phase profiles of an optical pulse, using time-lens operation.

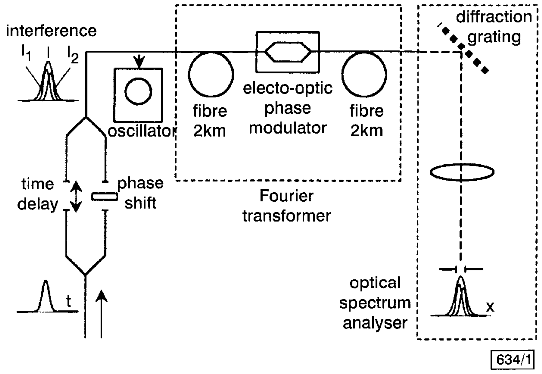

Fig. 1 *Schematic diagram of experimental system*

I_1, I_2: intensities of two shifted replicas of optical pulse

Principle of operation: The principle of the measurement can be explained by the known analogy between diffractive propagation of light beams in the paraxial approximation and propagation of narrowband pulses in dispersive media [9]. In this way, a sinusoidal phase modulation $\varphi = A\sin\omega_m t$ (A and ω_m are the modulation amplitude and frequency, respectively), for a narrow pulse (compared to $2\pi/\omega_m$), can function as a time lens that performs a phase modulation: $\varphi \simeq \omega_0 t^2/2f_t$, where ω_0 is the optical pulse frequency, $f_t = \omega_0/A\omega_m^2$ can be defined as the 'focal time'. According to the time-space analogy, two dispersive delay lines and a time lens can be used as a time Fourier transformer (see Fig. 1). Accordingly, the length of the fibre delay lines that provides the Fourier transform is: $L = 2\pi c/\lambda_0^2\,\omega_m^2\,|D|A$, where c is the speed of light, λ_0 the central wavelength, and D the group velocity dispersion of the fibre. A second Fourier transform, from time-to-space domain is performed by a spectrum measuring device. Note, that in this presentation, the measurement is similar to the time-to-space conversion given in [10, 11], but in our case the system is linear, and therefore simpler and more sensitive. A complete characterisation of an optical pulse is simply done by controlling the spatial beam wavefront in a spectrum measuring device. We use shearing interferometry, where the interference is performed between two replicas of the investigated wavefront, that are shifted by an amount Δx. Measuring the intensity profiles of both beams and the interference between them gives the phase difference $\Delta\varphi(x)$, where x is the transverse co-ordinate of the spatial beam. If Δx is small enough, then $\Delta\varphi \simeq (d\varphi/dx)\Delta x$. The measured phase difference can be used to reconstruct the phase profile $\varphi(x)$ and then the temporal phase $\varphi(t)$ of the analysed optical pulse.

Experiments and results: In our experiments, the optical pulses were formed with a continuous wave (CW) tunable semiconductor laser, an electrooptic phase modulator and a singlemode fibre, serially connected. The modulation frequency was 6.12 GHz, the pulse duration was of the order of 30 ps, and the total dispersion of the fibre was $DL = 416$ ps/nm. For the spectral measuring device we used a commercial optical spectrum analyser. The shearing interferometry, which was experimentally performed in the time domain, produced the spatial interference. In this case the spatial scale x is calibrated in units of wavelength λ. An all-fibre Mach–Zehnder interferometer was used to create two time-shifted replicas of the investigated optical pulse. The second electrooptic phase modulator (in the Fourier transformer) was operated at the same frequency as the pulse shaping modulator, but its voltage was phase shifted such that the light pulse in the modulator was at the centre of the time lens. The calculated total dispersion of both fibres in the transformer was $DL = -223$ ps/nm for $A = 2.4$ rad and $\lambda_0 = 1550$ nm.

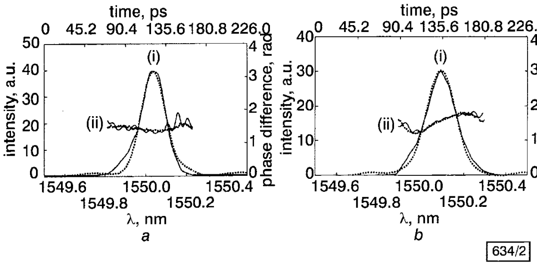

Fig. 2 *Measured intensity and phase difference*

a 25 km optical pulse shaping fibre
b 32 km optical pulse shaping fibre
(i) intensity
(ii) phase difference
——— by optical spectrum analyser
·········· by oscilloscope

The length of the fibre forming the original pulses in the first stage was chosen on the condition that the phase remains constant throughout the duration of the pulse. According to a simulation that we performed, this length was equal to 25 km. Fig. 2*a* shows the intensity profile and the phase difference $\Delta\varphi(t)$ measured with a spectrum analyser in a wavelength scale. For comparison, the same values measured in time domain with shearing interferometry and a sampling oscilloscope are also shown, showing a good agreement. Fig. 2*b* shows similar experimental results for the case where another 7 km was added to the fibre that shapes the original pulses. In this case, the simulation shows that the shaped pulses reach the maximum frequency chirp value. The Figure shows a good agreement between the measurements in the spatial and the time domain.

Discussion and conclusion: We have demonstrated a method for complete optical pulse characterisation based on time-lens operation. The proposed method has great importance for ultrashort optical pulses, where the resolution of photodetectors and oscilloscopes is not sufficient for measuring in the temporal domain. In the present method with the spectral device, the temporal resolution of the measurements is determined by the transform coefficient of the time and the wavelengths scales, $\Delta t/\Delta\lambda = |D|L$, where $|D|L$ is dispersion of the fibre in the Fourier transformer. In our measurements, the maximum resolution of the spectrum analyser of $\Delta\lambda = 0.01$ nm gives a temporal resolution of 2 ps. This resolution is limited by the amplitude of the phase modulator $A = 2.4$ rad. However, an increase of A, for instance to 51 rad [5], allows a decrease in $|D|L$ and the temporal resolution can reach the 100 fs regime. Additionally, use of a time lens operation based on nonlinear effects, as was done for intensity measurements [7], can lower this time to 10 fs.

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