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Ultrahigh-Bit-Rate Optical Sources and Applications

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Phil. Trans. R. Soc. Lond. A 1996 **354**, 719-731
doi: 10.1098/rsta.1996.0026

Ultrahigh-bit-rate optical sources and applications

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Various techniques are described for the generation of high repetition rate high-quality soliton pulse trains in the range 10 GHz–1 THz. Emphasis is placed on the technique of nonlinear conversion of an optical beat signal in dispersion-modified fibre. This can be achieved by a number of methods, including tapered or dispersion-decreasing fibre, step-like dispersion-profiled fibre and comb-like dispersion-profiled fibre. In addition, self-Raman scattering has been demonstrated as a powerful technique for ultrashort pulse generation and excellent mark space ratio operation. Techniques based on phase-modulated sideband extraction and direct modulation using electroabsorption modulators operating in the 10–60 GHz regime are also described.

1. Introduction

The mode-locked laser often appears an attractive and naturally applicable source for amplitude-modulated communications. With the ever increasing demand on telecommunication networks, the required bit rates are being constantly increased, and current transoceanic systems being installed will operate at 2.5 Gbit s^{-1}. However, over medium and short-haul spans, considerably higher bit rates will be required for the future, and if one neglects necessary modulation and considers for example only single-channel operation at a rate of 100 GHz, then device dimensions necessarily become small. For example, using either active or passive mode-locking, the laser is characterized by an output pulse train, the fundamental repetition rate of which is simply given by the inverse optical round trip time T of the cavity ($T = 2nL/c$, where n is the refractive index, c the speed of light and L the physical separation of the cavity reflectors). Therefore, at 100 GHz, a purely quartz-based configuration would have an overall length of 1 mm. Clearly, for bulk systems this leaves insufficient space for additional cavity elements, while conventional modulators are effectively restricted by electronics to operation at considerably lower frequencies anyway. Split-contact passively mode-locked semiconductor lasers can operate in this frequency range, but transform limited operation, although achieveable, can be difficult. Operation at up to 350 GHz has been demonstrated with these devices (Wu *et al.* 1993) but the system configuration is inflexible to variations in the pulse repetition rate.

Here we describe alternative mechanisms to generate high-bit-rate pulse trains based on nonlinear optical conversion schemes and more currently applicable schemes based on direct modulation in association with nonlinear compression. The former is based on the dual-frequency beat-conversion technique, where the repetition rate of the output pulse train is determined by the optical beat frequency of two single-frequency stabilized laser sources. In order to convert the sinusoidal beat frequency into a train of narrow optical pulses with a high mark-space ratio, it is necessary to amplify the beat signal to nonlinear (solitonic) power levels, and the subsequent propagation in optimally dispersion-profiled single-mode optical fibres gives rise to pulse evolution via the nonlinear interaction. The nonlinear conversion can be based on several techniques, some of which are described herein.

The crucial concept of the nonlinear beat-conversion technique was based on an idea by Tajima (1987) for the compensation of the temporal broadening experienced by solitons through propagation in optical fibres exhibiting loss. The soliton power is proportional to D/τ^2, where D is the group delay dispersion and τ the pulsewidth. On experiencing loss through propagation over a distance which is long compared to the characteristic soliton period, the solitons experience an exponential broadening of the pulsewidth with propagation distance (Hasegawa & Kodama 1981). Tajima suggested that if the dispersion of the fibre was constructed such that it exponentially decreased with increasing fibre length, then the broadening associated with the propagation loss could be compensated and the soliton would propagate with no temporal distortion. The required dispersion profile can be achieved through the construction of a fibre with a tapered core, since the group velocity dispersion can be precisely controlled via the size of the core diameter. Such a tapered fibre is equivalent to providing adabatic amplification, the action of which can be used to compress an input soliton structure with no energy loss to a dispersive wave. Dianov *et al.* (1989) were the first to propose the application of a dispersion-decreasing optical fibre to convert an optical beat signal into a train of fundamental solitons. Mamyshev *et al.* (1991) theoretically expanded and experimentally demonstrated the technique for the first time. Clearly, the dispersion-decreasing fibre used must be carefully selected to allow the compression required at the chosen repetition rate. The upper repetition rate is essentially limited by the input power requirement, while the lower repetition rate is limited by the fibre length. The lower repetition rates, by definition, require longer characteristic soliton lengths, while the maximum length is experimentally limited by the control of the minimum group-velocity dispersion. Note that at 20 GHz for a 5 ps soliton, the characteristic soliton period for a group delay dispersion of 1 ps nm^{-1} km^{-1} is approximately 700 km. The compression or output pulse width is determined by the total effective amplification. On the input side, it is essential to carefully control the input power, i.e. the input amplitude should be less than the amplitude of a fundamental soliton with a FWHM duration of $\frac{1}{2}T$, where T is the repetition time, and the amplification experienced over the length $(\frac{1}{2}T)^2$ should be small. The first realization of the technique, using diode laser inputs, was by Chernikov *et al.* (1992).

2. Dispersion decreasing fibre

Figure 1 shows a schematic of the experimental configuration of Chernikov *et al.* (1992). The beat signal was derived from two identical single-frequency DFB lasers operating at around 1530 nm. Through varying their relative temperatures, their wavelength separation could be varied by up to 2 nm. In this initial work, they were amplified to nonlinear power levels in a 20 m length of Er-doped fibre, pumped by the second harmonic (up to 600 mW average power) of a CW pumped mode-

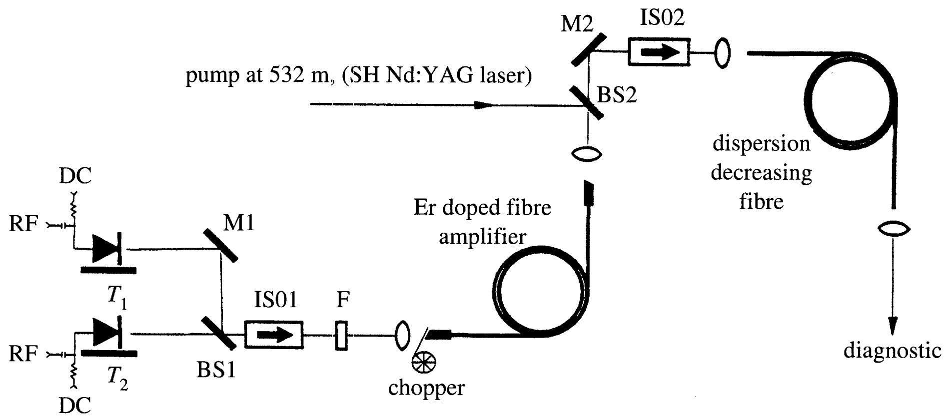

Figure 1. Schematic of original experimental configuration, employing dispersion-decreasing fibre for high-repetition-rate soliton generation using laser-diode nonlinear beat-signal conversion.

locked Nd:YAG laser. In order to increase the amplified signal power, the pump was chopped at a 500 Hz repetition rate with square pulses of *ca.* 1 ms duration, giving an increased gain factor of 8–10 times that using CW pumping. The tapered fibre manufactured at the General Physics Institute, Moscow (Bogatyrev *et al.* 1991), was approximately 2.2 km long with a loss of 0.6 dB km^{-1} and an optimized configuration giving a dispersion varying from 6.5 ps nm^{-1} km^{-1} at input to 1.1 ps nm^{-1} km^{-1} at the output at 1530 nm, limiting the possible compression.

The linewidth of the diode lasers was *ca.* 25 MHz; however, at the operational average power levels, stimulated Brillouin scattering (SBS) was in evidence, clearly limiting the efficiency of the conversion technique. In order to reduce the SBS, it was necessary to modulate the current to the diodes at a frequency *ca.* 100 MHz. It can be seen that two problems therefore exist with this technique. At the required power levels in the dispersion decreasing fibre, SBS is a limiting process, and its reduction through modulation of the source linewidth introduces phase noise on the generated signal. An additional problem associated with passive techniques is the difficulty in obtaining clock synchronization. This can be accomplished through the implementation of a high bandwidth phase-locked loop; however, the latency of the compression fibre can introduce additional complications to such a scheme. The initial experiments did, however, demonstrate, through varying the input power and wavelength separation, the possibility of generating pedestal-free fundamental picosecond soliton outputs, selectable in the range 80–130 GHz, with pulse durations varying from 3.0–1.5 ps and mark-space ratios of 4–7. Using the dispersion-decreasing fibre, the technique was further refined by Chernikov *et al.* (1992) and demonstrated at 70 Gbit s^{-1} for a completely CW-pumped system.

3. Step-like dispersion profiled fibre

The production of tapered dispersion-decreasing fibres requires precise control of the changing fibre core diameter with length, and fibres need to be selectively produced for specific repetition rates. It has been shown previously by Chi *et al.* (1991) that the split-step theoretical modelling of the soliton pulse transmission could be applied to the construction of a multi-segmented fibre of different and decreasing dispersion sections, optimally selected such that the overall profile presented ap-

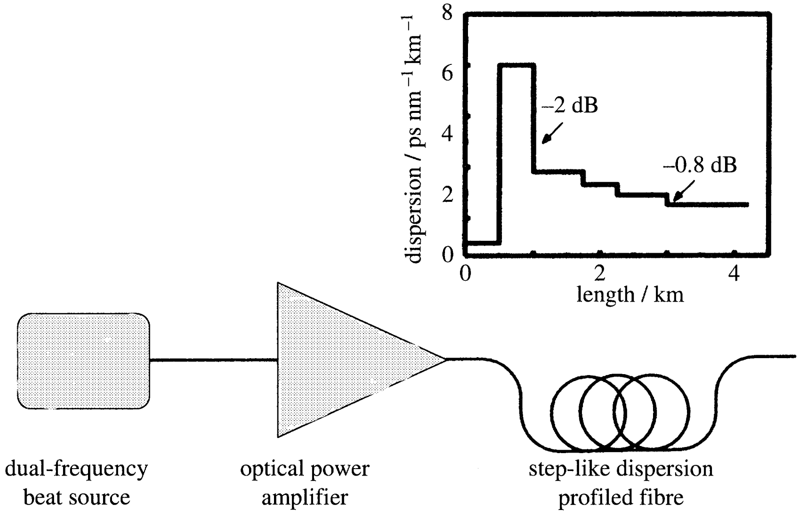

Figure 2. Schematic of the experimental configuration used to examine nonlinear beat-signal conversion in a step-like dispersion-profiled fibre. Inset shows the actual step-dispersion profile of the fibre employed.

proximated a fibre with an exponentially decreasing dispersion, and the application of such a step-like dispersion profiled fibre for soliton generation and compression was predicted by Mamyshev *et al.* (1991).

The experimental verification was undertaken by Chernikov *et al.* (1994) using a dispersion-profiled fibre, as shown in figure 2, in an experimental configuration which was a simple refinement on the scheme used with the dispersion-decreasing fibre. The beat signal source was similar to that described above and based on a pair of temperature tuned and stabilized single-frequency DFB lasers. The combined signal was amplified in a low-noise Yb-Er-doped fibre amplifier to an average power level of up to 800 mW and then launched into the step-like dispersion-profiled fibre (SDPF) (see figure 2).

The SDPF was constructed from six segments of dispersion-shifted fibre of different dispersions at the operational wavelength of 1553 nm. The first section was normally dispersive, 1 ps nm^{-1} km^{-1} and 500 m long. It was introduced to spectrally enhance the beat signal through four-wave mixing before soliton formation and compression in the following SDPF. An exponentially decreasing dispersion profile was approximated in the SDPF through the use of five optimimal-length fusion-spliced anomalously dispersive sections of dispersion-shifted fibre, 6, 1.9, 1.3, 0.9 and 0.5 ps nm^{-1} km^{-1}, respectively at 1553 nm. It was designed for operation around 100 GHz. For adiabatic conversion of the beat signal into a train of solitons without background, the relative variations of the dispersion from segment to segment should not exceed a ratio of 1.5. In order to compensate for the large variation between the second and third and between the fifth and sixth segments, it was necessary to introduce a step loss of −2.0 and −0.8 dB, respectively. This could be undertaken since the variations in dispersion can be analogously associated with a variation in the intensity of a soliton in the dispersion-profiled fibre and, as such, allows considerable leeway in the actual design of a SDPF for this application. Figure 3 shows a second-harmonic generation intensity autocorrelation trace (note the absence of any pedestal) of a 104 GHz repetition-rate pulse sequence, indicating the generation of deconvolved

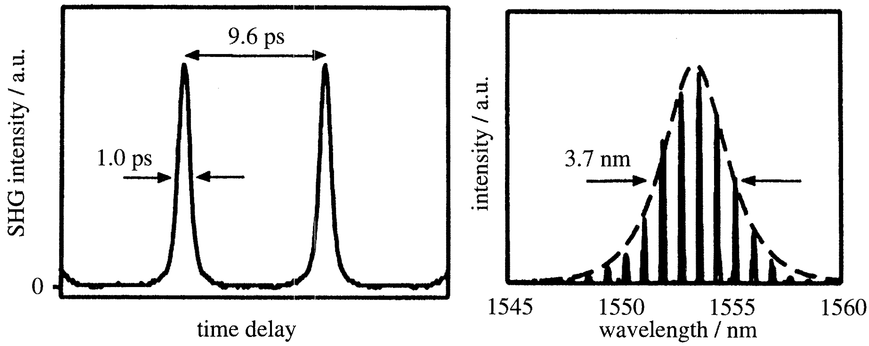

Figure 3. Autocorrelation trace and corresponding spectrum (indicating theoretical spectral shape of sech^2 profile) of 104 GHz repetition-rate pulses generated using the nonlinear beat conversion technique in a step-like dispersion-profiled fibre.

soliton pulses of 670 fs duration. This was obtained for an average input power of 400 mW. A sech^2 profile has been fitted to the corresponding spectrum recorded and, with a measured bandwidth of 3.7 nm, gives a time bandwidth product of 0.31. Due to the large ratio of the input to output dispersions, a relatively large compression ratio was achieved and a mark space ratio of 1:14 was measured. It was possible to tune the repetition rate in a 10 GHz range while still maintaining the high quality of pulses and mark-space ratio.

4. Comb-like dispersion-profiled fibre

The step-like dispersion profiled fibre offers system-design flexibility through the use of optimized lengths of differing dispersion fibres. Additional optimization and flexibility can be achieved through the use of a comb-like dispersion profiled fibre, where the effects of dispersion and nonlinearity can be separately treated and optimized. Optical solitons are stable to perturbations in two extremes. In one, the adiabatic regime, the perturbation to the soliton takes place over a length scale which is long compared to the characteristic soliton length. In the other, the so-called average soliton regime (Mollenauer *et al.* 1991; Hasegawa & Kodama 1990; Kelly *et al.* 1991) stability is exhibited provided the length scale of any perturbing effect, be it gain or dispersion, etc., is short compared to the soliton length. In the comb-like dispersion-profiled fibre both situations are addressed. The dispersion and nonlinear contributions essentially of each step are separately addressed. Experimentally, this is achieved by alternating short segments of high anomalous dispersion together with longer lengths of very low dispersion at the operational wavelength. In this way the dispersion profile of the fibre resembles that of a comb. In the low dispersion section, the effects of nonlinearity (self-phase modulation) dominate, while in the shorter highly anomalously dispersive section it may be neglected, but pulse compression and chirp correction is significant. Within the average soliton model however, an average dispersion of the the two sections may be considered, while, overall, an adiabatic pulse compression takes place due to the designed decreasing function of this dual-section-averaged dispersion. This approach has the advantage in that both nonlinearity and dispersion can be separately considered and optimized. The technique was first considered both theoretically and experimentally by Chernikov *et al.* (1993*a*, 1994). For stable compression, the nonlinear phase shift over each segment of the composite fibre should not exceed $\frac{1}{2}\pi$.

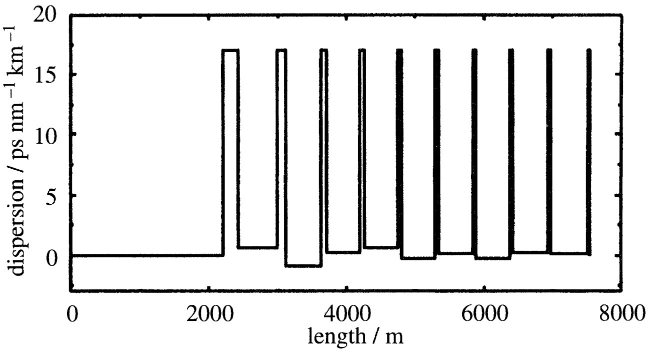

Figure 4. Dispersion profile of an experimental comb-like dispersion-profiled fibre used in the beat-frequency conversion technique, to generate fundamental soliton pulse trains in the 60 GHz regime.

Figure 4 shows the dispersion profile of the experimental comb-like dispersion-profiled fibre (CDPF) employed. It was constructed from 20 segments of standard telecommunications fibre (STF) and dispersion shifted fibre (DSF), spliced together and alternating DSF-STF-DSF-STF-DSF$\cdots$etc. The measured splice loss was *ca.* 0.1 dB, which needed to be accounted for in the overall design and proposed compression. Also, requiring consideration was the average fibre propagation loss of *ca.* 0.25 dB km^{-1}. The lengths of the DSF segments are determined by the input power level, while provided that the length of the STF sections are considerably less than the DSF segments, then the length of the STF sections is determined by the beat frequency. This is in contrast to the dispersion-decreasing fibre, where the input power and fibre length depend on the square of the repetition frequency. Therefore, the CDPF allows considerable flexibility in the system design and permits significant expansion of the upper and lower limits of the practical frequency range. In the experimental configuration, the length of the DSF sections was in the range 500–600 m, while the STF sections varied from 220 to 30 m to permit the monotonically decreasing average dispersion profile required. The nonlinear phase shift in each section was less than $\frac{1}{2}\pi$. Like the SDPF, there is also an added advantage in the use of various lengths of dispersion-shifted fibre of differing dispersion-zero wavelengths. The dispersion shifting is undertaken by varying the germanium content. For example, in the CDPF described above, five different DSFs were used with germanium concentrations varying between 8 and 14%. However, the frequency shift due to Brillouin scattering is dependent on the germanium concentration, being measured as 89 MHz wt%$^{-1}$ (Tkach *et al.* 1986). Therefore, the cascading of various relatively short lengths of fibres of differing germanium content inhibits the buid-up of stimulated Brillouin scattering, since a germanium doping difference of *ca.* 0.5% should be sufficient to prevent overlap of the SBS gain spectra. At the input side of the CDPF, two 1.1 km lengths of DSF, with different dispersion zero, were included to reduce the problem of SBS.

Conceptually, the other parts of the experimental configuration employing the CDPF were similar to those described above. However, the actual configuration was a totally integrated fibre device. The dual-frequency source was based on coupled-cavity single-frequency fibre lasers incorporating intracore fibre Bragg gratings as the cavity reflectors (Chernikov *et al.* 1993*b*). A schematic of the overall experimental configuration is shown in figure 5. The coupled-cavity fibre laser was 1.65 cm in total length and provided a dual-frequency output, without mode hops, centred around

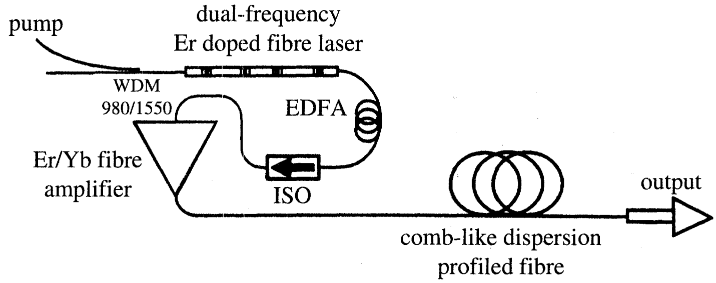

Figure 5. Integrated all-fibre configuration for the production of high-repetition-rate fundamental soliton pulse trains employing a comb-like dispersion-profiled fibre.

1545 nm with a selected frequency separation of 59.1 GHz. The long-term measured average linewidth was *ca.* 16 kHz, which was effectively instrument limited, and the stability of the dual linewidth was also instrumentation limited, measured as 3 MHz. Pump radiation not required in the pumping of the dual-frequency source was transmitted and used to pump a following Yb:Er fibre preamplifier, the output of which was further amplified in a following Yb:Er power amplifier, giving an average power in the beat signal of up to 200 mW. This was then converted in the integrated CDPF into a train of high-quality fundamental solitons, which exhibited no detectable pedestal or intrapulse noise. The measured pulse duration was measured to be 2.2 ps, corresponding to a mark-space ratio of 1:7.7 and indicated the suitability of the technique for high-repetition-rate pulse-train generation in an integrated all-fibre configuration. Through the use of additional segments it is also possible to increase the mark-space ratio.

5. Raman self-scattering

One of the most efficient nonlinear effects discovered in optical fibre is stimulated Raman scattering (SRS) (Stolen & Ippen 1973). The Raman gain curve of fused quartz is maximum for a frequency shift of *ca.* 440 cm^{-1}; however, it exhibits a broad gain profile with a half width greater than 400 cm^{-1} and significant gain can be obtained even for modest frequency shifts. Generally, for femtosecond pulses, dispersion severely limits the Raman conversion process, but for solitons propagating in the anomalously dispersive regime and with low net dispersion, it is possible for the high-frequency components of the spectrally broad femtosecond soliton to provide significant gain for the low-frequency components, which leads to an asymmetric spectrum and a continuous evolution in the long-wavelength region of the spectrum as the pulse propagates (Dianov *et al.* 1985; Mitschke & Mollenauer 1986). The effect is generally known as the soliton self-frequency shift and in the most general case this self-pumped low-frequency shift continues until the power in the pulse is insufficient to maintain the soliton condition, since most usually the dispersion (and associated soliton power required) increases with wavelength. The addition of amplification or dispersion modification can, however, change this and arrest early self-termination.

On the simplest level, it can be seen that once, for example, ultrashort pulse solitons have been formed, or are forming within a dispersion-decreasing fibre or one of its modifications, then the self-frequency shift should play a significant role. Chernikov *et al.* (1993*c*) first reported this technique in combination with a dispersion-decreasing fibre to generate low-repetition-rate pulsed trains containing 250 fs soliton pulses at

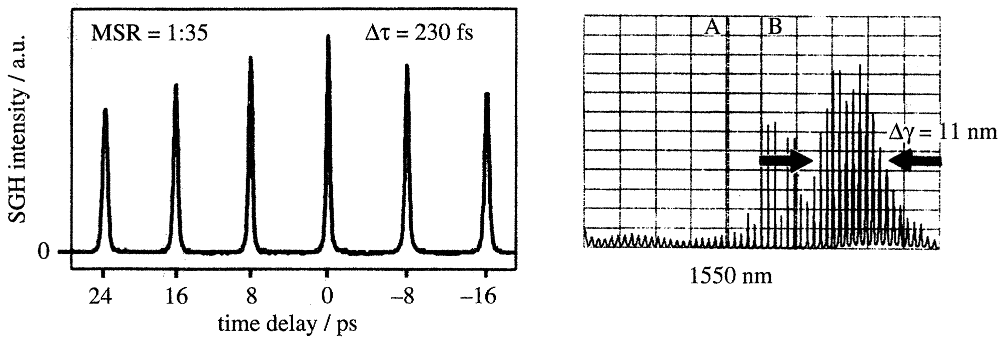

Figure 6. Autocorrelation trace of 230 fs solitons at 125 GHz repetition rate obtained via beat conversion in association with self-frequency shifting techniques. The complementary 11 nm halfwidth spectrum (5 nm div^{-1}) can be seen distinct from the input carrier around 1555 nm.

114 GHz. We have developed this technique and, in association with high power Yb:Er amplifier technology, have demonstrated a truely CW 1 THz soliton pulse source. The experimental configuration utilized two DFB diode lasers to generate a 125 GHz beat signal at 1555 nm which was pre- and power amplified in diode pumped Yb:Er fibre amplifiers to an average power level of 1.0 W. This was launched into a 1.6 km long dispersion-decreasing fibre with an input and output group-delay dispersion of 10 and 0.5 ps nm^{-1} km^{-1}, respectively. Continuous trains of 230 fs soliton pulse were obtained, with an exceptionally high mark-space ratio of 1:35. An autocorrelation trace of the output train is shown in figure 6, together with the associated spectrum, where the 11 nm bandwidth ($\Delta\nu\Delta\tau = 0.310$) of the Raman self-frequency shifted pulses is distinct from the remaining input carrier around 1555 nm.

In order to generate a pulse train at a repetition rate of 1 THz, a polarization division multiplexing technique was employed, using bulk optics. The 125 GHz pulse train was made to be incident on a calcite crystal such that the input polarization was at 45° to the optic axis. For a crystal of 7.68 mm thick, the e- and o-rays temporally separate by 4 ps. Thus, the input 125 GHs signal can be converted to 250 GHz. Each of the pulses so generated can be further subdivided by a second calcite crystal of half the thickness of the original, and with its optic axis rotated by 45° to that of the first crystal. By cascading three crystals, with the third having a thickness of 1.92 mm, and placing these between crossed polarizers, an efficient eight-times multiplexer can be constructed. Figure 7 shows an autocorrelation trace of a 250 GHz and a 1 THz multiplexed pulse train. It should be noted that the average power in these is in excess of 100 mW, and currently developed diode pumped Yb:Er amplifiers should readily allow average power levels well in excess of 1.0 W.

6. Modulation sideband extraction techniques

As previously mentioned, the problems of ease of clock synchronization and phase noise in the above conversion techniques, although solvable, detract from the simplicity of the source. One method to overcome this, described by Swanson *et al.* (1994), is based on sideband extraction of a frequency-modulated single-frequency source. This can be seen with reference to our experimental configuration shown in figure 8. A single frequency DFB laser operating around 1562 nm (figure 8, left-hand spectrum) was coupled into a fibre pigtailed lithium niobate phase modulator, which was driven at 10 GHz. This allowed efficient sideband generation of up to eight side-band orders

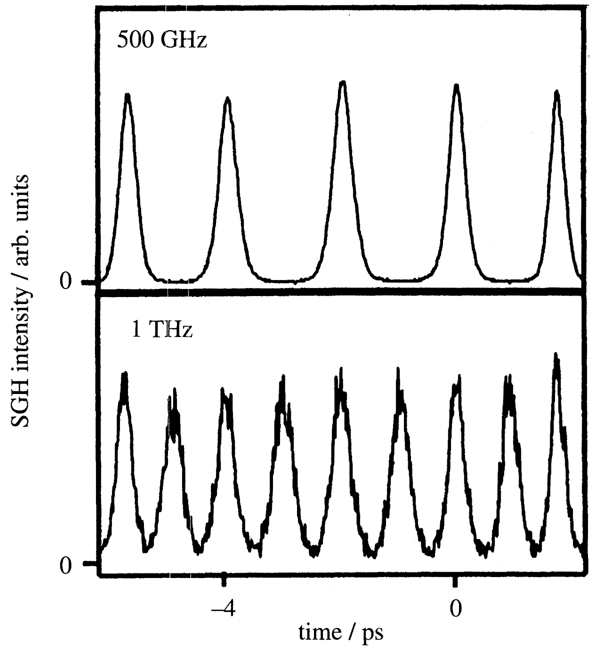

Figure 7. Autocorrelation traces of 250 GHz and 1 THz pulse trains, generated using polarization multiplexing.

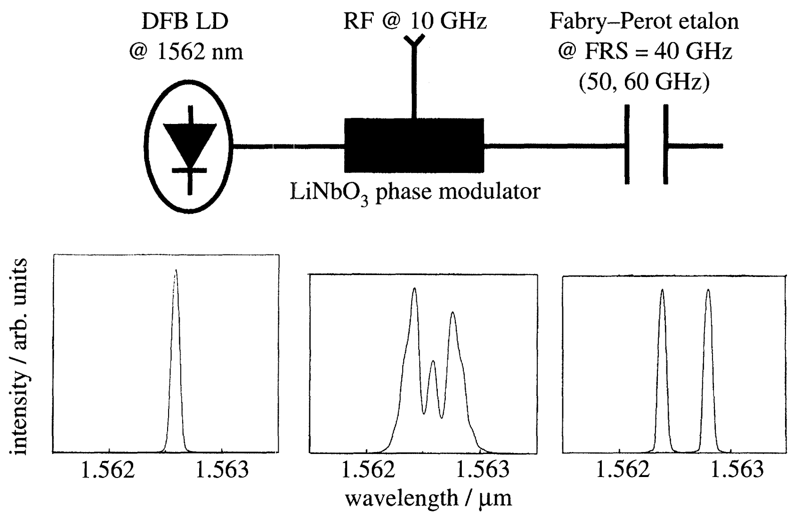

Figure 8. Schematic of sideband extraction configuration and related spectra.

(figure 8, resolution-limited spectrum, centre). Through using an inline Fabry–Perot etalon with a free spectral range in the experimental situation shown of 50 GHz, although this can be constructed for any side band extraction frequency separation, two stable phase-locked single frequencies were extracted (figure 8, right-hand side), which on subsequent amplification and conversion in a CDPF can produce a stable soliton source with a synchronous 10 GHz electronic clock signal.

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7. Electroabsorption modulator applications

As in optical communications, direct modulation techniques provide the simplest and potentially the most applicable method for short-pulse generation and control. Over the past few years, electroabsorption modulators have attracted considerable interest, with modulation depths greater than 30 dB for only a few volts applied, and have been shown to be capable of generating short pulses at up to 30 GHz. One problem with these devices is that, generally, the generated pulses are not transform limited and some form of chirp compensation is required following the modulator. Recently, pulses as short as 6.3 ps at 10 GHz have been produced (Moodie *et al.* 1994) by using a dispersion-compensating fibre, and with a duty ratio of 6.3%, time-division multiplexing readily allowed the production of data rates of 40 Gbit s^{-1}. Some problems can be introduced through the application of a dispersion-correcting fibre, such as phase and polarization drift if the temperature and birefringence are not actively controlled. We have recently developed an alternative geometry, replacing the fibre with a chirped fibre Bragg grating (Kashyap *et al.* 1993) and demonstrating a versatile source of ultrashort pulses as short as 5.8 ps at 10 GHz directly out of the grating corrector, and with nonlinear compression have generated soliton pulses as short as 200 fs.

Figure 9 shows a schematic of the experimental arrangement. A DFB laser operating at 1.5625 μm and an average power level of 1 mW was coupled into an InGaAsP multiple quantum well electroabsorption (EA) modulator. This was supplied with a reverse bias of 7.5 V and driven at 10 GHz by a sinusoidal peak-to-peak voltage signal of 8 V into 50 W. The pulses generated were amplified in a diode-pumped Yb:Er preamplifier and chirp compensated by a thermally chirped fibre Bragg grating of 1.75 nm bandwidth incorporated in a low-loss transmission filter based on a polarization-dependent polarization coupler (Guy *et al.* 1994). This permitted the production of transform-limited pulses of duration 5–6 ps. These were amplified to an average power level of *ca.* 200 mW in a second diode-pumped Yb:Er fibre amplifier. Following transmission through a 1 km length of standard telecommunications fibre, were compressed in a 1.6 km length of dispersion decreasing fibre, which had a dispersion at 1.55 μm varying from 10 ps nm^{-1} km^{-1} at input to 0.5 ps nm^{-1} km^{-1} at the output. Figure 10 shows a representative second-harmonic generation autocorrelation of the pulses and their associated spectrum. From the latter, it can be seen that SRS dominated the process and the carrier frequency distinct from the broader soliton spectrum is apparent. One clear advantage of this is that the carrier can be readily removed simply by spectral filtration, for example with an in-line Bragg grating. The time bandwidth product of the 187 fs pulses was measured to be 0.32. On a logarithmic intensity trace, a small (less than 0.5%) pedestal was shown to be present on the pulses.

As previously mentioned, the dispersion-decreasing fibre is designed for a particular input pulse duration and does not allow significant deviation from the design criteria. Therefore, variation in the output pulse duration is not particularly flexible. However, spectral filtration within the spectrum of the 200 fs soliton does permit the production of transform-limited wavelength-tunable pulses, and, through varying the bandwidth of the spectral filter pulse duration, selectable picosecond and femtosecond high-repetition-rate pulses. Figure 11 shows the autocorrelation trace and the corresponding spectrum of a 2 ps pulse at 1.568 μm. The time bandwidth product and curve fitting indicate a sech^2 (soliton-like) profile to the pulses gener-

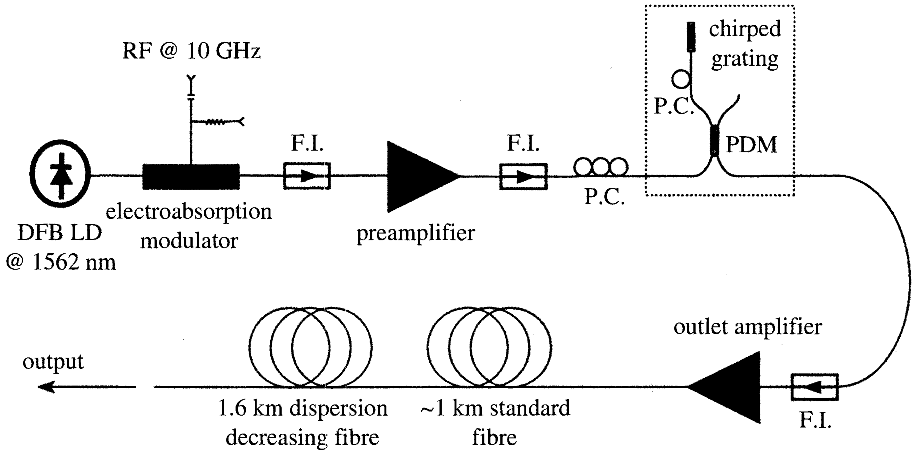

Figure 9. Experimental configuration of scheme for soliton pulse generation based on direct modulation of CW source using an electroabsorption modulator, chirp compensation and nonlinear conversion.

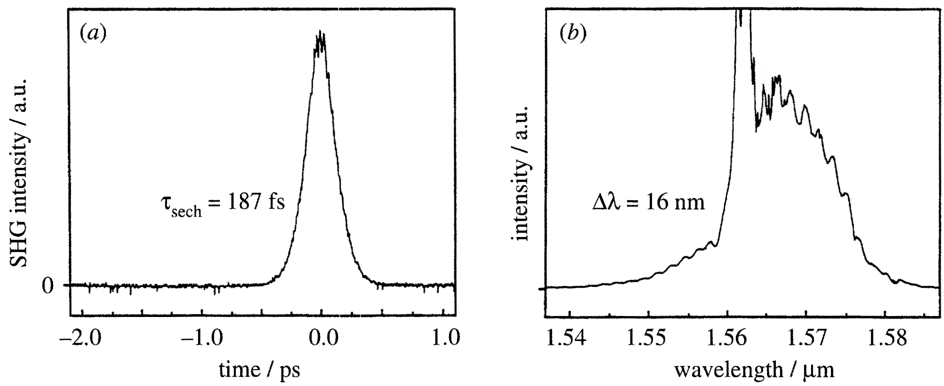

Figure 10. Autocorrelation trace of femtosecond pulses and their corresponding spectrum generated using the nonlinear conversion of dispersion-compensated pulses from an electroabsorption modulator source at 10 GHz repetition rate.

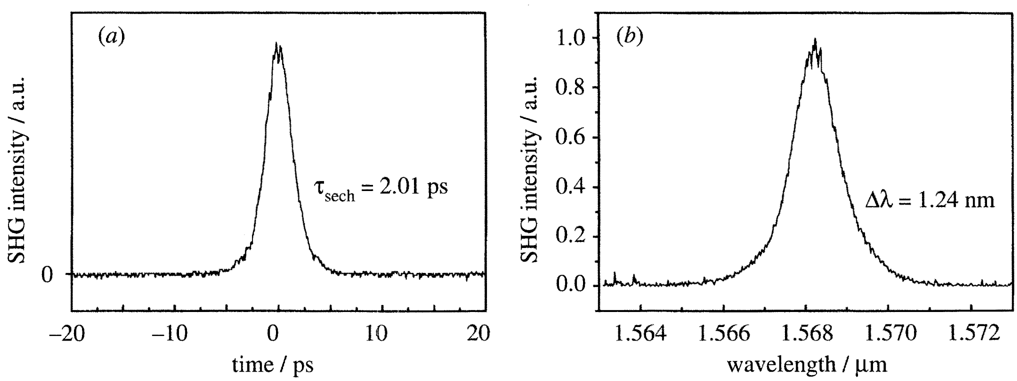

Figure 11. Autocorrelation trace and spectrum of tunable picosecond 10 GHz pulses extracted from femtosecond soliton spectrum (see figure 10).

ated in this way. We are currently investigating this technique of spectral slicing for the extraction of several WDM soliton channels for ultrahigh capacity transmission.

Space limitations prohibit description of the numerous and diverse application of the high-repetition-rate pulse trains generated by the techniques described above. They have been applied to investigations of dispersion compensation using in-fibre chirped Bragg gratings at transmission rates above > 100 GHz (Kashyap *et al.* 1994). Currently, we are using the pulses in studies of ultrafast processes and limits of switching in semiconductor amplifiers (Manning *et al.* 1994), and applications of these in ultrahigh-bit-rate dispersion compensation techniques (Ellis *et al.* 1995).

We are grateful to the SERC and the EPSRC for their financial support of the research reported in this paper. We would also like to express our sincere thanks to IRE Polus and in particular Dr V. P. Gapontsev for his continued support and provision of high-power diode-pumped Yb:Er fibre amplifiers, without which much of this research could not have been undertaken.

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