Duration-tunable 0.2–20-ps 10-GHz source of transform-limited optical pulses based on an electroabsorption modulator

S. V. Chernikov, M. J. Guy, and J. R. Taylor
Femtosecond Optics Group, Department of Physics, Imperial College, Prince Consort Road, London SW7 2BZ, UK

D. G. Moodie and R. Kashyap
BT Laboratories, Martlesham Heath, Ipswich IP5 7RE, UK

Received May 24, 1995

A 10-GHz source of pulse-width-tunable bandwidth-limited optical pulses operating near 1.55 μm based on an electroabsorption modulator and a tunable-dispersion chirped fiber Bragg grating is described both experimentally and theoretically. The pulse-width range attainable from this device is significantly extended through the exploitation of nonlinear adiabatic solitonlike pulse compression and spectral filtering.

© 1995 Optical Society of America

Sources of transform-limited short pulses at 1.55 μm operating at an ~10-GHz repetition rate are currently of interest for high-capacity telecommunications. Techniques based on the direct modulation of a cw laser are seen to be the most practical solution. The generation of short pulses at repetition rates up to 20 GHz has been demonstrated by gain switching of a distributed-feedback laser diode. Another technique is based on the modulation of a cw distributed-feedback laser diode with an external high-speed LiNbO₃ Mach–Zehnder amplitude modulator. The implementation of a phase modulator in conjunction with spectral filtration was also proposed and demonstrated recently for generation of transform-limited pulses. Pulse generation with a high-speed electroabsorption modulator (EAM) electrically driven with a sinusoidally varying bias has attracted a lot of interest recently and is seen to be one of the best high-bit-rate short-pulse sources.

A problem associated with several of the direct modulation techniques is difficulty in producing trains of transform-limited, pedestal-free pulses with a low duty ratio, which is vital for optical time-domain multiplexing systems and optical processing. With a multiple-quantum-well EAM with dispersion-compensating fiber, a 10-Gbit/s train of transform-limited pulses with a duty ratio as low as 0.063 was recently demonstrated. To compress the pulses, and hence further to reduce the duty ratio, it is possible to employ nonlinear compression in a dispersion-decreasing fiber (DDF).

We report a 10-GHz repetition-rate system based on an EAM capable of generating high-quality transform-limited pulses with a duration tunable in the range ~20–0.2 ps. The experimental setup, shown in Fig. 1, has been described in detail previously. The EAM was driven electrically with a dc reverse bias of up to 8 V and a variable-amplitude sinusoidal rf modulation at 10 GHz with an estimated maximum peak-to-peak voltage of 8 V into 50 Ω. The duration, chirp, and background level of the pulses measured directly after the modulator are dependent on the rf and dc voltage supplied to the modulator. The dependence of the pulse duration on the dc voltage for (different) fixed rf voltages without chirp compensation is indicated by dashed curves 1 and 3 in Fig. 2(a). Although the shortest pulses were generated at the highest dc bias, they were accompanied by a large background level (~30%). Note that the background is due to the finite modulation depth of the device used, and a modulator with a higher extinction ratio will yield pulses with a lower background level (see, e.g., Ref. 5). The background was significantly suppressed at lower bias voltages, but the generated pulses were chirped. To compensate for the chirp and to generate transform-limited pulses with low background after the EAM, a low-loss dispersive transmission filter was used. It was based on an 8-mm-long temperature-chirped fiber Bragg grating. We could adjust the dispersion of the grating by tuning the temperature gradient. The dispersion of the grating is determined by the reflection bandwidth according to $D = 9.6L/\Delta \lambda$ (nm), where $L$ is the length of the grating and $\Delta \lambda$ is the grating bandwidth. The two solid curves in Fig. 2(a) show the duration-dc bias dependence for the case of chirp compensation with a positively chirped grating with bandwidths of 1.0 nm (curve 2) and 1.5 nm.
the supplied rf and dc (generated directly after the EAM is determined by shown in Fig. 3. The nature of the pulses generated at 1562 nm, as reported in Ref. 9) of the EAM. The chirp parameter (measured with the technique of the measured transmission characteristic and the dispersion of the chirp compensator for a given indication the existence of optimum values of the dc bias and had the minimum background. These results, on dispersion without and with dispersion compensation, were repeated for a range of grating bandwidths resulted in transform-limited (T.L.) pulses with time-bandwidth products of 0.32 and low background levels were generated. These measurements were repeated for a range of grating bandwidths with the rf voltage optimized in each case to ensure the minimum pulse duration and lowest background level. Figure 2(b) shows the optimized pulse durations and the compression ratio resulting from the use of the chirp-compensating grating. In all cases the generated pulses had time-bandwidth products of ~0.32 and had the minimum background.8 These results indicate the existence of optimum values of the dc bias and the dispersion of the chirp compensator for a given level of rf power supplied to the EAM.

The results obtained can be interpreted by use of the measured transmission characteristic and chirp parameter (measured with the technique reported in Ref. 9) of the EAM at 1562 nm, as shown in Fig. 3. The nature of the pulses generated directly after the EAM is determined by the supplied rf and dc (V_{DC}) voltages, and this can be expressed as

\[ V = V_{DC} - V_M \cos(2\pi f_M t), \]

where \( E_0 \) includes the insertion loss of the EAM, \( f_M \) is the modulation frequency, and \( \Delta \beta \) is a complex modulation coefficient. \( \Delta \beta(V) \) can be expressed as \( \Delta \beta = \Delta \kappa + i\Delta n \), where \( \Delta \kappa \) and \( \Delta n \) are the real and imaginary parts of the modulation coefficient, corresponding to amplitude and phase modulation, respectively. The nonlinear dependence of \( \Delta \kappa \) on the driving voltage can be well approximated by a linear ramp function for values of \( V \) between \( V_1 \) and \( V_2 \), as shown by the dotted curve in Fig. 3.

\[ \Delta \kappa(V) = \Delta \kappa(V_1) + \frac{V - V_1}{V_2 - V_1}(\Delta \kappa(V_2) - \Delta \kappa(V_1)), \]

\( \Delta n(V) = \Delta n(V_1) + \frac{V - V_1}{V_2 - V_1}(\Delta n(V_2) - \Delta n(V_1)) \)

These approximations allow the evaluation of the chirp parameter and the compression ratio after dispersion compensation. For a large enough dc bias (V_{DC} > V_2), the cosinusoidal modulation of voltage may be expanded about the peak modulation value and the imaginary part of the modulation coefficient approximated by a linear function such that \( \Delta n(V) = \Delta n(V_1) + \frac{V - V_1}{V_2 - V_1}(\Delta n(V_2) - \Delta n(V_1)) \).

Equation (1) then reduces to

\[ E(t) = E_0 \exp[-\Delta \kappa(V_{DC} - V_M)] \times \exp[-0.5(\Delta \kappa + i\Delta n)(2\pi f_M t)^2]. \]

This represents a Gaussian pulse shape envelope, and it is now possible to calculate all the essential parameters:

\[ \Delta t = \frac{\ln 2}{(\pi^2 f_M^2 V_M \Delta \kappa)^{1/2}}, \]

\[ \psi = \sqrt{1 + \alpha^2} \quad (\alpha = \partial n/\partial \kappa), \]

\[ D = 2\pi c \Delta t^2/\lambda^2 4 \ln 2 \psi, \]

\[ B = 20 \log e \Delta \kappa(V_2 - (V_{DC} - V_M)) + 10 \log \psi. \]
where $\Delta t$ is the pulse duration before chirp compensation, $\psi$ is the compression factor attained, $D$ is the optimum dispersion for chirp compensation, and $B$ is the background level ($B = 10 \log I_{\max}/I_{\min}$). From Eq. (7) and Fig. 3 it can be seen that the minimum voltage should be somewhere just above $V_1 \approx 1.7V$ (i.e., $V_{DC} - V_M \approx V_1$) to provide the best modulation depth. A larger value will cause a lower modulation depth, resulting in a relatively higher background level. This criterion means that the dc bias must be $V_{DC} = V_M + 1.7V$ to provide the optimum pulse generation that was achieved in the experiment [Fig. 2(b)]. In this case the chirp parameter $\partial n/\partial k$ (shown in Fig. 3) is $2\sim3$, and Eq. (5) then explains the constant compression factor of $\sim 2.5$ observed in the experiment [Fig. 2(b)]. Equation (4) shows that the compressed pulse duration for the optimum pulses generated is given by $\Delta t$ (ps) $\approx 4.7/[V_{DC}(V) - 1.5]^{1/2}$, in good agreement with the theory. The dependence of the compressed pulse duration on the chirped grating bandwidth shown in Fig. 2(b) may be well fitted by $\Delta t$ (ps) $\approx [0.021\Delta \lambda$ (nm) $- 0.007]^{1/2}$, also in excellent agreement with the predictions of Eq. (7). According to Eq. (7) the background level should be below 25 dB. In fact in the experiment even better background suppression was achieved as the result of filtration of the carrier frequency by the grating.\(^8\)

The simple theoretical treatment outlined above is based only on the measured EAM characteristics, and it gives an accurate prediction of optimum dc and rf driving voltage and the necessary dispersion of the chirp compensator for generation of transform-limited pulses within the range of tunability.

The system described above generated transform-limited pulses in the range $\sim 20\sim5$ ps. For generation of shorter pulses a nonlinear pulse compression technique was used. The $\sim 5$-ps pulses generated at the output of EAM chirp compensator were amplified to a power level of $\sim 200$ mW and propagated through $\sim 1$ km of standard fiber followed by 1.6 km of DDF. After experiencing adiabatic compression through solitonlike pulse shaping, the pulses had a duration of $\sim 190$ fs and a spectral width of $\sim 14$ nm, resulting in a time–bandwidth product of 0.32.\(^7\)

As the design of the DDF is optimized for a specific input pulse duration and power, it is not possible to tune the duration of the output pulses significantly simply by adjusting the launched power or duration. We found, however, that spectrally filtering the 190-fs output pulses from the DDF could generate high-quality longer pulses. Initially a tunable fiber-pigttailed multilayer interference filter with a FWHM bandwidth of $\sim 2.5$ nm was spiked to the output. This resulted in pulses with a duration of $990$ fs and a spectral bandwidth of 2.59 nm, indicating that the output pulses were still transform limited. Splicing on a second, identical filter resulted in 2.0-ps pulses with a bandwidth of 1.24 nm, again indicating a transform-limited sech\(^2\) pulse profile. Figure 4 shows the autocorrelation trace and (inset) a log scale spectrum of these pulses. The use of other filters should permit the production of any pass bandwidth, and hence pulse duration, required, from 180 fs to $\sim 4$ ps. A spectral slicing technique has also been demonstrated\(^10\) that uses this source to generate a number of 10-GBit/s wavelength division multiplexing channels.

This research was partly funded by the Engineering and Physical Sciences Research Council (UK). We thank the IRE-POLUMS Company for the loan of the amplifiers used in these experiments.

References


