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SUBPICOSECOND (320fs) PULSES FROM CW PASSIVELY MODE-LOCKED EXTERNAL CAVITY TWO-SECTION MULTIQUANTUM WELL LASERS

T. Schrans, R. A. Salvatore, S. Sanders and A. Yariv

Indexing terms: Semiconductor lasers, Lasers, Pulse generation

Pulses from a passively mode-locked two-section multiquantum well laser coupled to an external cavity are compressed to subpicosecond pulse widths using an external grating telescope compressor. A minimum deconvolved pulse width of 0·32 ps is measured, close to the transform limit, with peak powers of 1·9 W.

In the preceding 10 years considerable interest has been given to the generation of subpicosecond pulses from semiconductor lasers [1–9], resulting in pulses as short as 0·21 ps after compression for electrically pumped hybrid mode-locked semiconductor lasers with an external saturable absorber [8]. We recently demonstrated passive mode locking of external cavity two-section quantum well lasers, with a monolithically integrated saturable absorber [10, 11]. These lasers are broadly tunable [12], but emit pulses longer than 3 ps, with time–bandwidth products greater than 3, indicating that strong chirping may be present. In this Letter we report external compression of these pulses to subpicosecond pulse widths, obtaining near transform limited spectra and a minimum deconvolved pulse width of 0·32 ps. To our knowledge this is the shortest pulse duration reported for multisection mode-locked semiconductor lasers.

The laser used in our experiment is a quadruple quantum well two-section buried heterostructure GaAs laser, similar to those used in our previous experiments [10–12], mounted in an external cavity configuration as shown in Fig. 1. The facet facing the external cavity is antireflection (AR) coated to less than 5%, and the other facet is high-reflection (HR) coated to 90%. The absorber section is grounded through a 100 Ω resistor, and the gain section is pumped with a DC current source. The output of the laser is taken from the 70% mirror, and sent through a singlepass grating telescope compressor [13], to access both signs of chirp. The light coming out of the compressor is directed to a collinear second harmonic intensity autocorrelator and a monochromator, for optical spectrum measurements.

All measurements were performed with the laser mode locked in the first harmonic of the external cavity round-trip frequency (558 MHz) [10], which was obtained for gain currents between 39 and 48 mA. The pulse durations are very sensitive to the cavity alignment, with different pulse widths coinciding with small spectral changes. Fig. 2 shows the full width half maximum (FWHM) of the intensity autocorrelation at different gain currents and different cavity alignment for the uncompressed pulses. For a fixed cavity alignment the FWHM tends to increase with gain current, as does the

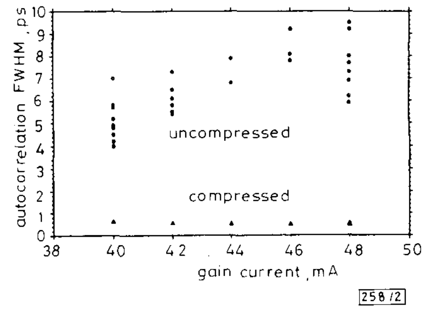

Fig. 2 *Intensity autocorrelation FWHM as function of gain current and different cavity alignment*

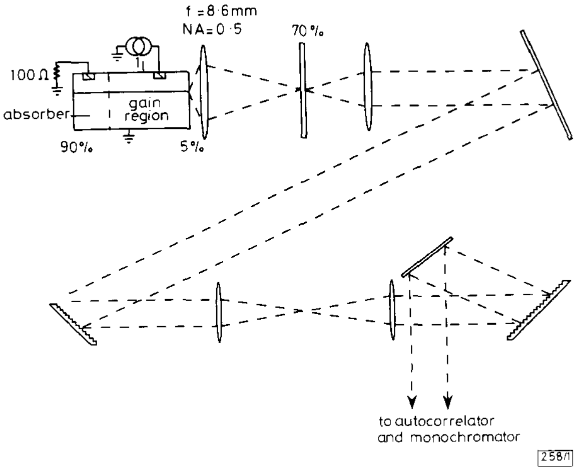

Fig. 1 *Two-section laser passively mode locked in external cavity with external grating telescope compressor*

optical bandwidth, resulting in higher time-bandwidth products at higher gain currents. The optical bandwidth was typically 1·1 THz, corresponding to time–bandwidth products greater than 3, which is more than nine times the hyperbolic secant transform limit of 0·31.

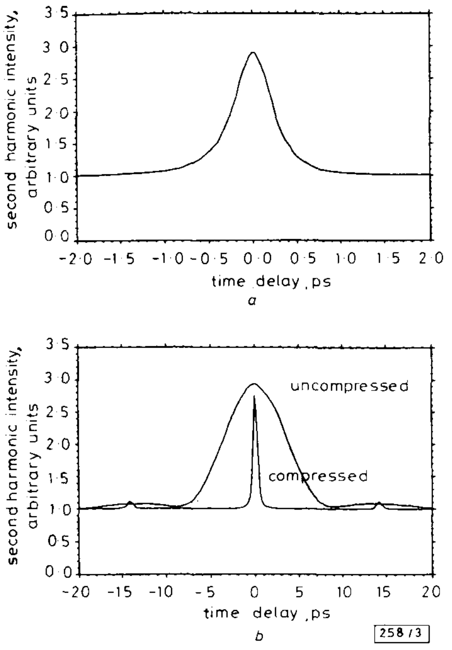

Fig. 3 *Second harmonic intensity autocorrelation, I = 46 mA*

a Compressed pulse at high resolution
b Uncompressed and compressed pulse at low resolution

The minimum compressed pulse FWHM was typically 0·36 ps (all pulse widths are deconvolved assuming a hyperbolic secant pulse shape) (Fig. 2) with an optical bandwidth of 1·1 THz, giving a time–bandwidth product of 0·39. Pulses with an FWHM as low as 0·32 ps were measured for a gain current of 48 mA, with an optimised cavity alignment. An autocorrelation trace of a 0·33 ps compressed pulse for a gain current of 46 mA is shown in Fig. 3*a*. The uncompressed pulse autocorrelation is shown in Fig. 3*b* and has an FWHM of 5·2 ps and a time–bandwidth product of 6·8. The large compression by a factor of more than 15 indicates that the pulses have a strong linear chirp, which is due to the saturation of the carrier density in the absorber and the gain section. All compressed pulses were obtained with the compressor in the region of negative group velocity dispersion, corresponding to a chirp toward shorter wavelengths during the pulse. Satellite pulses are observed at a time delay of 14·2 ps, corresponding to the round-trip time between the two facets of the 510 μm long laser. The satellite pulses contain less than 10% of the total pulse energy, and are attributed to the relatively high AR coating [12, 14]. Streak camera pictures of the compressed pulse show a weak pulse trailing the main pulse by 14 ps, as well as a weak pulse preceding the main pulse by 14 ps. The optical spectrum of the compressed pulse is shown in Fig. 4, and has an FWHM of ~3 nm (1·2 THz) giving a time–bandwidth product of 0·41, which is close to the transform limit. An interferometric autocorrelation was measured for the compressed pulse, and is shown in Fig. 5. The interferometric fringes are visible over the full pulse width, indicating that the pulse is near transform limited. The optical spectrum shows a strong modulation at 71 GHz, the round-trip frequency between the two semiconductor facets. Compression to near transform limited pulses shows that the residual reflectivity at the AR coated facet does not prevent mode locking over a bandwidth larger than the 71 GHz semiconductor mode spacing, although it does cause weak satellite pulses. Typical pulse energies coming out of laser were 1·3 pJ for a gain current of 46 mA. Losses in the compressor reduced this to 0·6 pJ per pulse, which corresponds to a peak power of 1·9 W for a 0·33 ps pulse.

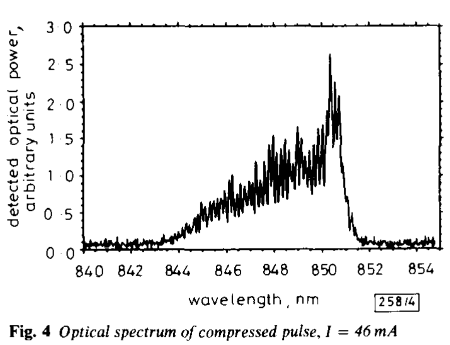

Fig. 4 *Optical spectrum of compressed pulse, I = 46 mA*

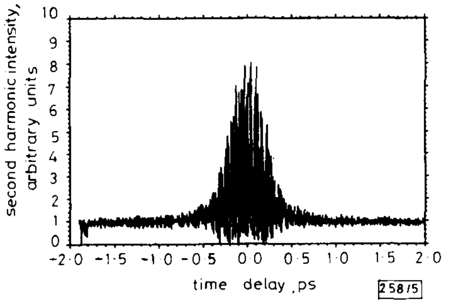

Fig. 5 *Second harmonic interferometric autocorrelation of compressed pulse, I = 46 mA*

In conclusion we have compressed pulses from a passively mode-locked two-section multiquantum well laser coupled to an external cavity to subpicosecond pulse widths using an external grating telescope compressor. The pulses have a duration as short as 0·32 ps, are near transform limited with time–bandwidth products around 0·4, and have peak powers just under 2 W.

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SPECTRAL CHARACTERISATION AND FRAME SYNCHRONISATION OF OPTICAL FIBRE DIGITAL PPM

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Indexing terms: Optical communication, Optical modulation, Synchronisation

The discrete time decoding of data in pulse position modulation calls for accurate timing synchronisation, particularly at the frame rate. In the Letter, for the first time the spectral properties of optical fibre digital PPM are considered. An original expression is presented for predicting the spectrum and it is shown that, unlike satellite PPM, a component exists at the frame rate which may be used for timing extraction purposes. Further, it is illustrated that the modulation index can be used to enhance this component by up to 19 dB. This has been verified practically, with the results agreeing to within 1 dB of those predicted from the original expression presented.

Introduction: Digital pulse position modulation (PPM) has been investigated and optimised in terms of sensitivity for the optical fibre channel [1, 2]. These studies have shown that PPM outperforms PCM by up to 12 dB. However, the problem of synchronisation has not been addressed for the optical fibre channel. The importance of achieving accurate timing synchronisation in PPM is seen to be far more important than in PCM as the temporal position of the pulse conveys the information as opposed to the pulse presence or absence. Consideration has been given to timing synchronisation in PPM for the free space channel [3], however the system structure is different to that of the optical fibre channel. We present a characterisation of the optical fibre PPM spectrum based on its cyclostationary properties. We show that unlike satellite PPM, optical fibre PPM can exhibit discrete components at the frame repetition rate. Further, we compare frame synchronisation in free space and optical fibre PPM and show that whereas the former uses extra signal processing in the form of tracking back to back pulses [3] the latter can use the modulation index to achieve and enhance frame synchronisability.

Spectral characterisation: We consider a stochastic sequence t_k that is wide sense stationary, representing the incoming data, and which is to be coded into PPM. The resulting time domain PPM process $x(t)$ is then given by

$$x(t) = \sum_{k=-\infty}^{\infty} g(t - kT_f - t_k) \tag{1}$$

where $g(t)$ is the pulse shape employed and T_f the PPM frame duration. The PPM frame structure is such that M bits of information are represented by a single pulse in one of $n = 2^M$ time slots in the frame. A guard band at the end of each frame serves to avoid interframe interference. The ratio of the duration of the n slots to the frame duration defines a modulation index m. Because the wide sense stationary t_k sequence is processed by the repetitive framing operation, the PPM sequence $x(t)$ can be treated as a cyclostationary stochastic process [4]. The power spectral density PSD of these processes can be determined by first evaluating the autocorrelation function and then invoking the Wiener–Khintchine principle. Owing to space limitation, we present here the final expression for the autocorrelation; a detailed discussion will be given in a separate publication. The autocorrelation is given by

$$R(\tau) = \frac{1}{T_f}\left\{\rho(\tau) + \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty}\left[\sum_{j=0}^{N-1}\beta_j\,\rho\left(\tau - \frac{jT_f}{N} - kT_f\right)\right]\right\} \tag{2}$$

where $\rho(\tau)$ is the correlation due to the pulse shape $g(t)$. $\bar{\beta} = \bar{a} \otimes \bar{a}$ is the cyclic correlation of the frame probability distribution $\bar{a}$. Invoking the Wiener–Khintchine theorem gives the new expression for the PSD of the optical fibre PPM pulse stream:

$$S(f) = \frac{1}{T_f}\,|G(f)|^2\left[1 - \sum_{l=-\infty}^{\infty} B\left(f - \frac{lN}{T_f}\right)\right] + \frac{1}{T_f^2}\left[\sum_{k=-\infty}^{\infty}\left|G\left(\frac{k}{T_f}\right)\right|^2 B_s\,\delta\left(f - \frac{k}{T_f}\right)\right] \tag{3}$$

where $G(f)$ is the Fourier transform of the pulse shape $g(t)$, B is the modulus squared of the characteristic function of the data distribution, and s is a selector given by $s = (k + N/2) \bmod (N) - N/2$.

Results: The expression in eqn. 3 shows that the PPM spectrum consists of two parts, a continuous and a discrete part, as given by the first and second terms, respectively. The shape of the continuum is dictated by the combination of the pulse shaping effect and the effect of the periodic $B(f - lN/T_f)$ function. $B(f - lN/T_f)$ is a continuous function Fourier synthesised with weights equal to β_j the cyclic correlation of the frame probability distribution, it is periodic with period equal to lN/T, the PPM slot duration. In brief, it accounts for the random signalling format of PPM. The second term clearly shows the presence of discrete components at the optical fibre PPM frame repetition rate. The presence and magnitude of these components are affected by the pulse shape, the modulation index and the data probability distribution. The effect of the last two is embedded in B_s which is the modulus squared of the characteristic function due to the probability distribution $\bar{a}$ on the frame. In our approach, and for the sake of integrity, we consider a constraint on the pulse shape similar to that used on optimising the system sensitivity [2], namely PPM pulse durations that are independent of the modulation index. In this case and for all practical pulse shapes the presence of the frame rate component will be independent of the pulse shape. This leaves the dependence on the data probability distribution and the modulation index.

Practically, an extreme case arises in free space PPM [3] where the modulation index is inherently unity and the data probability distribution (if uncoded) is uniform. In this case B_s is the Fourier transform of a uniform probability distribution, hence the result is a sinc function whose zeros coincide with